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PROBLEMS OF SPACE BIOLOGY

Volume 7 — Operational Activity, Problems
of Habitability and Biotechnology

V. N. Chernigovskiy, Editor

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V. N Chernigovskiy, Editor

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ABSTRACTS

Problems of the Reliability of Man in Spacecraft Control Systems. P.K. Isakov, V.A. Popov, M.M. Sil'vestrov. Problems in Space Biology, Vol. 7, p. 3, 1967.

The operator-spacecraft system, a closed multicircuit system, is discussed. The need for a wide use of terrestrial laboratories for the investigation of the reliability and efficiency characteristics of the operator is stressed. The basic problems for solution by means of models of the man-machine system, simulating not only the control process but also conditions creating the particular state of the man-operator, are noted. Refs. 4.

Some Aspects of Activity of Sensory Systems as Applied to Problems of Space Physiology. V.D. Glezer, V.A. Koslyakov, V.A. Kozhevnikov, V.N. Chernigovskiy, L.A. Chistovich. Problems in Space Biology, Vol. 7, p. 8, 1967.

Problems connected with the obtaining and processing of information and the diagnosis of sensory forms are discussed. Experimental data are presented on orientation in space, diagnosis of visual forms and of the sounds of speech. These problems are analyzed as they apply to spacecraft control. Figs. 8.

Psychophysiological Characteristics of the Solution of Motor Problems by Man. N.A. Rokotova. Problems in Space Biology, Vol. 7, p. 22, 1967.

Grouping of motor acts during learning and performance of assigned sequences was studied. Grouping is the central mechanism of operational programs, and the group of actions is an element of the operational program. The temporal organization of a sequence of human actions is examined. During frequent repetition of a series of learned movements the performance time, both of the whole series and of its component groups of movements and separate motor acts, varies within small limits. The argument is put forward that the temporal organization of human actions is connected with the presence of an internal rhythmic process assigning the regular rhythm of work. Tables 5. Figs. 10, Refs. 34.

On Certain Features of Programming a Sequence of Human Actions. N.A. Rokotova, I.M. Gorbunova. Problems in Space Biology, Vol. 7, p. 51, 1967.

The role of grouping in learning and performance of an ordered sequence of human actions was studied. Grouping determines both the course of learning and the character of performance of the sequence of actions. It is postulated that a group of actions describable by a common characteristic is an element of the operational program. Tables 6. Figs. 3. Refs. 7.

Nerve Control of the Tempo of Motion in Man and Possible Methods of Representing Time in the Nervous System. N.A. Rokotova. Problems in Space Biology, Vol. 7, p. 64, 1967.

Control of the tempo of movements by the human nervous system is examined as a control over two functions. The first of these describes the level of maintenance of the tempo. The second function alters the tempo. The normal human adult can maintain any performance tempo of his own choice with

great precision. A change in tempo by a certain amount and maintenance of the new tempo are possible. The accuracy of performance, describable as $\delta t/t = \text{const.}$, while a change in tempo by a minimal amount, describable as Δt , is controlled by a function bearing a logarithmic relationship to the original tempo. Tables 3. Figs. 5. Refs. 11.

Organization of a System of Actions in the Case of Random Alternation of Signals. Ye. S. Rogovenko. Problems in Space Biology, Vol. 7, p. 75, 1967.

The object of this investigation was to study how man organizes a system of four actions (pressing on keys arranged in a row) under the conditions of a random order of two equally probable signals, when two actions were connected with each signal.

To organize their system of actions all the subjects used the method of seeking rules for their choice of decisions. At first they divided all the actions into two groups connected with each signal, then established rules for changes between actions within the limits of the group on repetition of the signals, while at the end of learning rules were formed for changes between actions belonging to different groups with a change in the signal. When establishing connections between actions the subjects combined changes performed with the same order of the signals into a rule for working with this order. The phenomenon of transfer of the rule of working established for repetition of one signal to the case of repetition of the other signal was observed in most subjects. Tables 2. Figs. 3. Refs. 11.

Organizing a System of Actions with Random Alternation of Signals, Search and Choice of Actions. Ye. S. Rogovenko. Problems in Space Biology, Vol. 7, p. 84, 1967.

The object was to examine how man forms a system of actions under the conditions of a random order of two equally probable signals if allowed to choose his own concrete actions and switch from one to another. Subjects were instructed to work at a problem on a switchboard with 12 keys arranged 4 in a row.

During training most subjects reduced the number of their actions to 4. The design of the switchboard enabled the subjects to organize a system of actions in a two-dimensional space. During formation of a system of actions under these conditions the subjects used the method of seeking reference points and switching between them so as to compose a complete symmetrical figure on the surface of the switchboard. Table 1. Figs. 4. Refs. 5.

Comparative Speeds and Variability of Motion of the Fingers of Man. I. D. Bogina. Problems in Space Biology, Vol. 7, p. 94, 1967.

Movements of each finger (tapping on a teletype switchboard) of both hands by 3 subjects at three speeds chosen by the subjects were studied: fast, optimal, slow. Essential differences were found between the intervals of the mean duration of the movements at different speeds. High correlation exists between the various fingers of the subject's two hands at a given speed. Great similarity also is found between mean values of duration of movements by different subjects at a given speed. There are grounds for supposing that the movement cycle is a more highly organized interval than its component elements, and that for rapid

and optimal imprinting the interval of the movement cycle is evidently assigned. Tables 8. Fig. 1. Refs. 8.

Effector Activity of a Human Being in Fixing Performance Time. I. M. Gorbunova and N. A. Rokotova. *Problems in Space Biology*, Vol. 7, p. 109, 1967.

In investigations on human subjects performing a sequence of actions in a set time interval high accuracy of work was found. The error of performance did not exceed 5% of this interval. The error committed during performance of the sequence could be compensated in the next operation. The presence of compensation depends on the magnitude of the error but not on its sign. Compensation of error took place by a change in work tempo, i. e., by a change of a definite amount in the movement cycle either throughout the sequence or in its first and second halves.

It is postulated that the mechanism of compensation of errors is associated with two-dimensional tracking of signals conveying information about time—an external signal and the frequency of the subject's own movements. Tables 8. Figs. 5. Refs. 15.

Characteristics of the Biomechanics of Elementary Human Motion Under the Condition of Weightlessness and G-Loading. L. V. Chkhaidze, I. A. Kolosov, V. I. Lebedev, I. F. Chekirda, A. V. Yeregin, A. D. Burchuladze, V. I. Stepanov. *Problems in Space Biology*, Vol. 7, p. 129, 1967.

Under conditions of brief (not more than 30 sec) weightlessness and during overloads (not exceeding 2 units, duration 15-18 sec), the biomechanics of human movements (slow flexion and extension of the elbow and of the laden and unladen hand, slow flexion and aimed extension of the same joint and rapid flexion and sudden, unaimed extension in the same joint) was studied cyclogrammetrically. In weightlessness the actual muscular effort needed to perform the corresponding elements of the coordinated structure of the studied movements falls to 50%, and in overloads of up to 2 units it rises. Increased activity of the nervous centers correcting performance of skilled movements is observed. Figs. 6. Refs. 7.

The State and Efficiency of a Human Being During Prolonged Confinement in a Spacecraft Simulator (S. G. Zharov, A. Ye. Baykov, I. I. Kas'yan, A. P. Kuz'minov, D. G. Maksimov, V. F. Onishchenko, and V. A. Popov). *Problems in Space Biology*, Vol. 7, p. 141, 1967.

Data for the general state and working ability of man during a 12-day stay in a simulated spacecraft are described. Reliability of the work of man as an operator falls under these conditions. Changes are observed also in his general state (stagnant exaltation of the α -rhythm, decrease in amplitude of ECG waves, slowing of atrioventricular conduction, diminution of bioelectrical activity of muscles, weakening of the orienting reflex, and so on). Changes are particularly marked if the subjects, after the experiment, were exposed to overloads on a centrifuge or did physical exercises by running on a moving tract. Figs. 4. Refs. 16.

Maintenance of a Given Static Force While the Force of Gravity is Transformed. M.A. Cherepakhin. Problems in Space Biology, Vol. 7, p. 151, 1967.

A human skilled movement was studied experimentally during flights by a jet aircraft along a parabola of weightlessness..

Maintenance of a static effort during periodic transformation of gravitational force in the presence of visual control took place accurately, but in the absence of such control accuracy of maintenance of the assigned effort depended on the subjects' body weight. During exposure to overloads a tendency was observed for the effort to increase if the overload vector coincided with the direction of effort, but in weightlessness the effort was reduced. The bio-electrical activity of the investigated muscles increased slightly during overloads of under 1.5-2 units and during performance under visual control, but rose sharply in weightlessness. Biopotentials of the postural muscles decreased sharply in weightlessness but rose slightly during overloads. Table 1. Figs. 2. Refs. 3.

Contribution to the Problem of Oculogravic Illusion. L. A. Kitayev-Smyk. Problems in Space Biology, Vol. 7, p. 157, 1967.

It is suggested that oculogravic illusions arise as a result of afferent impulses denoting changes in the oculomotor apparatus compensating tonic influences of gravity receptors on it. The oculogravic illusion is regarded as part of an illusory distortion of visually perceived space arising under the influence of gravitation. Fig. 1.

Optical Illusions in Man in the Case of Weightlessness and of the Combined Effects of Weightlessness, Angular and Coriolis Acceleration. L.A. Kitayev-Smyk. Problems in Space Biology, Vol. 7, p. 162, 1967.

The onset of illusory changes in the form of visual objects in a number of subjects is described during weightlessness created in an aircraft during flights along a parabolic trajectory. With the onset of partial weightlessness immediately after absence of gravitational force, these illusions disappeared. During the combined action of weightlessness and radial or Coriolis acceleration the visual illusions in some subjects were of a special character. On the basis of comparison of illusions described in this work with known clinical and experimental data a possible mechanism is suggested for the visual disturbances arising in weightlessness. Fig. 1.

Physiological-Hygienic Evaluation of the Life-Support Systems of the "Vostok" and "Voskhod" Spacecraft. G.I. Voronin, A.M. Genin, A.G. Fomin. Problems in Space Biology, Vol. 7, p. 170, 1967.

Hygienic and technical problems of life support in spacecraft are analyzed. The life-support system described maintained the parameters of the gaseous medium within limits of: pressure from 750 to 755 mm Hg, temperature from +19 to +20°, humidity from 62 to 69%, O₂ concentration from 21 to 22%, CO₂ from 0.4 to 0.6%. Table 1. Figs. 3.

Effect on the Organism of Prolonged Confinement (100 days) in a Pure Oxygen Atmosphere at Overall Pressure of 198 mm Hg. N.A. Agadzhanyan, Yu.P. Bizin, G.P. Doronin, A.G. Kuznetsov, A.R. Mansurov. Problems in Space Biology, Vol. 7, p. 181, 1967.

Hygienic and physiological aspects of a long stay in an atmosphere of pure oxygen are discussed. Actual experimental data relating to a stay of 100 days in an atmosphere of pure oxygen with a total pressure of 198 mm Hg are given. Refs. 12.

Certain Functions of the Central Nervous System and Gas Exchange During Prolonged Confinement of Animals in a Hyperoxic Helium Environment. A.G. Zhironkin, G.V. Troshikhin. Problems in Space Biology, Vol. 7, p. 189, 1967.

Defensive conditioned reflexes were studied in mice during a stay of 20 days in an atmosphere rich in oxygen (60%). Considerable delay in conditioned reflex formation was found in animals kept in a helium-oxygen medium. Figs. 2. Refs. 11.

Human Reaction to Hypoxia and Hypercapnia When Breathing Nitrogen and Helium-Oxygen Mixtures. I.S. Breslav, Ye.N. Salatsinskaya. Problems in Space Biology, Vol. 7, p. 193, 1967.

The investigation was carried out on men and women aged 18-25 years, using the gas-preferendum method. Under normal and hypoxic conditions the subjects preferred helium mixtures. They reacted negatively to a mixture with 2.5-6% CO₂ in an atmosphere of helium, but not to it in an atmosphere of nitrogen. Tables 2. Figs. 2. Refs. 9.

Physiological Effect of the Replacement of Nitrogen in the Air by Helium in the Case of Oxygen Deficiency and High CO₂ Concentrations. A.G. Dianov. Problems in Space Biology, Vol. 7, p. 200, 1967.

During the experiment the body temperature, respiration rate and pulse rate were measured. Replacement of the nitrogen of the air by helium had a beneficial effect on the responses of the animals under conditions of hypoxia and hypercapnia. Tables 3. Figs. 5. Refs. 16.

Some Peculiarities of the Speech Function in a Changed Gas Medium. V.S. Kuznetsov. Problems in Space Biology, Vol. 7, p. 211, 1967.

The characteristics of speech formation were investigated in subjects staying for 10-22 days in a helium-oxygen atmosphere. In a medium containing 21% oxygen, 2-4% nitrogen and up to 75% helium, speech showed an increase on the average of 0.7 octave in the pitch of formants and a fairly high degree of punctiliousness, which is attributed to the richness of the Russian language, and it is maintained by the high intensity of acoustic and vocal compensatory mechanisms. Table 1. Fig. 1. Refs. 9.

Respiration of Oxygen at High Pressure, Features of and Training for Such Respiration and the Physiological Basis. V.A. Skrypin. Problems in Space Biology, Vol. 7, p. 217, 1967.

A critical analysis of the problem of oxygen breathing under increased pressure is given. The physiological basis of the training program is discussed. Refs. 12.

The Effect of Physical Training Under Normal and Increased Partial Oxygen Pressure on the Stability of White Mice to Transverse Gravitational Acceleration and Hypoxia. P.V. Vasil'yev, N.N. Uglova. Problems in Space Biology, Vol. 7, p. 226, 1967.

Static or dynamic physical training is an effective method of increasing resistance of the body to the action of radial accelerations and to a lowered partial pressure of oxygen. Particularly high survival rates were obtained when physical training was combined with exposure to hypoxia. Tables 6. Refs. 22.

Effect of a Different Rate of Growth of Anoxia on the Vegetative Functions and Bioelectric Activity of the Brain of a Developing Organism. I.G. Dallakyan, G.M. Nikitina. Problems in Space Biology, Vol. 7, p. 234, 1967.

Dynamics of EEG changes was studied in rabbits in relation to changes in autonomic functions (respiration and cardiac activity) during development of hypoxia at two rates (1 and 15 m/sec) in animals of different ages. In young rabbits (not more than 20 days old) at the rate of 2 m/sec the altitude ceiling is 13,000 m, and at 15 m/sec 11,000 m. This difference disappears with age. At the rate of 2 m/sec respiration is affected first, then bioelectrical activity of the brain, followed by cardiac activity. At 15 m/sec this order was found only in older animals. In the early stage of ontogenesis autonomic changes arise simultaneously. In older rabbits at the rate of 15 m/sec, profound qualitative changes were found in the ECG. Figs. 6. Refs. 15.

The Influence on Man of a Long Stay Under Conditions of Reduced Barometric Pressure and Relative Isolation. D.I. Ivanov, V.B. Malkin, I.N. Chernyakov, V.V. Popkov, Ye.I. Popkov, A.B. Flekkel', G.A. Arutyunov, V.G. Terent'yev, P.V. Buyanov, G.G. Sturua, N.A. Vorob'yev. Problems in Space Biology, Vol. 7, p. 246, 1967.

The effect of a long (from 10 to 30 days) stay by two persons in a small pressure chamber (5 m^2) was studied. Altogether 7 subjects took part in the experiments. The partial pressure of oxygen in the pressure chamber was maintained between 150 and 200 mm Hg, and of carbon dioxide between 2 and 14 mm Hg. The total gas pressure in the chamber (O_2 , CO_2 , N_2 , water vapor) corresponded to altitudes of 3000, 5000, and 7000 m. For each subject a specific program of daily activity was assigned. Frequency characteristics of the EEG were within limits of diurnal physiological variations. On the ECG the cardiac axis was displaced to the left (at an altitude of 7000 m). The pulse rose regularly, on the average by 10-15 beats/min, and excitability of the cardiovascular system was increased. Basal metabolism fell by 15-20%. The content of 17-hydroxycorticosteroids in the 24-hour urine increased. The serum

albumin fraction was increased and the globulins decreased. A program based on waking at night was less favorable. Table 1. Figs. 8. Refs. 8.

Effect of Adaptation to High Mountain Conditions on Human Resistance to Acute Hypoxia and High Temperature. V.B. Malkin, G.D. Yukhnovskiy. Problems in Space Biology, Vol. 7, p. 257, 1967.

The effect of adaptation to high altitudes (2000-4200 m) on resistance to acute hypoxia and a high external environmental temperature (+70°) was studied in clinically healthy young men.

After a stay in the mountains, an increase in the altitude ceiling was found in 13 of 15 subjects in the mountains for the first time when raised by degrees in the pressure chamber. The increase amounted to 1000-20,000 m. This effect was absent in mountaineers shown by a control investigation to possess high background resistance. After their return from the mountains most of the subjects showed a slight decrease in resistance to high external environmental temperatures. Table 1. Figs. 2. Refs. 6.

Adaptation to Hypoxia as a Means of Increasing Human Resistance to Radial Acceleration. A.R. Kotovskaya, P.V. Vasil'yev, R.A. Vartbaronov, S.F. Simpura. Problems in Space Biology, Vol. 7, p. 265, 1967.

The effect of adaptation to high altitudes on the resistance of 7 mountaineers and 8 persons not adapted to high altitudes to the action of radial accelerations (+G_x) was studied during spinning on a centrifuge. After a stay in the mountains tolerance to overloads was increased in all the mountaineers and in 6 of the subjects undergoing adaptation for the first time. In one of two subjects showing no increase in tolerance to overloads, signs of mountain sickness developed during their stay in the mountains. Physiological reactions of the cardiovascular and respiratory systems of most of the hypoxia-adapted subjects to overloads were rather more marked than in the controls.

The authors consider that the suggested method is effective enough for the purpose of increasing man's resistance to the action of overloads. Table 1. Figs. 2. Refs. 17.

Continuation of Investigations of Changes in Osmotic Resistance of Erythrocytes During Acclimatization to High Mountain Conditions. Z.I. Barbashova. Problems in Space Biology, Vol. 7, p. 270, 1967.

Cyclic changes in osmotic resistance of the erythrocytes in human blood were found during acclimatization in the mountains. On the first days after arrival in the mountains a significant increase in erythrocyte resistance was found in 25 of 26 subjects. Later during the stay the osmotic resistance of the erythrocytes became normal in most subjects, but rose again in the first days after descending to sea level. Table 1. No refs.

Effect of Hyperoxia on Dynamics of Erythropoiesis in Animals. A.M. Shmeleva, I.S. Breslav. Problems in Space Biology, Vol. 7, p. 275, 1967.

Experiments were performed on CC57W pure-line mice and Wistar rats.

Under the influence of an oxygen-enriched atmosphere an increase in the reticulocyte count and a slight decrease in the erythrocyte count and hemoglobin level were found in the animal's blood. A long stay of the animals in the hyperoxic atmosphere caused a transient increase in the erythrocyte count. In the after-period the erythrocyte count fell and the acid resistance of the erythrocytes rose. Figs. 6. Refs. 14.

Possibility of Reducing the Toxic Action of Carbon Dioxide on the Living Organism. V.P. Zagryadskiy, O.Yu. Sidorov, E.K. Sulimo-Samuylo. Problems in Space Biology, Vol. 7, p. 282, 1967.

The possibility of reducing the toxic action of carbon dioxide on the body by increasing the percentage of oxygen in the inspired air, administration of a group of vitamins, and nonspecific training is discussed. Table 1. Fig. 1. Refs. 10.

Human Adaptation to Temperature Conditions with the Object of Increasing Resistance to Heat. P.V. Buyanov, A.V. Beregovkin, M.A. Migulina. Problems in Space Biology, Vol. 7, p. 288, 1967.

Familiarizing procedures should be carried out in order to determine individual resistance to high temperatures. The use of specific methods of increasing heat resistance is not acceptable and is limited to the influence which they exert on vascular tone. Table 1. Refs. 16.

Standards for Noise Levels in Cabins of Spacecraft During Long-Duration Flights. E.M. Yuganov, Yu.V. Krylov, V.S. Kuznetsov. Problems in Space Biology, Vol. 7, p. 296, 1967.

A series of experiments was carried out to determine the effect of high-pitch (up to 3000 Hz) noise with a total level of 60-65 and 74-76 dB and exposure of between 8 h and 60 days on the human auditory analyzer. Isolation hypokinesia, and the conditions of work, rest, food, clothing, etc., were simulated. After an exposure of 8 h moderate fatigue of auditory function was noted, after exposure of 24 h a decrease in auditory sensitivity. Continuous exposure to noise (75 dB) for 30 days had an adverse effect on the CNS and the auditory analyzer.

However, noise of 60-65 dB, acting for 60 days, had no effect on the auditory analyzer. This value was recommended as permissible for spacecraft. Refs. 20.

Auditory Function in Man After a Period of Several Days in an Artificial Atmosphere. Yu.V. Krylov. Problems in Space Biology, Vol. 7, p. 304, 1967.

Auditory function was investigated in human subjects staying many days at a lowered barometric pressure (308 mm Hg) with normal partial pressure of oxygen; they were exposed to an atmosphere containing up to 2% CO₂ and breathed a helium-oxygen mixture. No deviations exceeding the normal physiological variations were found during dynamic audiometry and investigation of

the time of retrograde adaptation of hearing. The considerable resistance of the human auditory analyzer during a stay of many days in an artificial atmosphere was noted. Fig. 1. Refs. 10.

Biological Action of Intense Wide-Band Noise on Animals. V.I. Ponomar'kov, A.Yu. Tysik, V.I. Kudryavtseva, A.S. Barer, V.K. Kostin, V.Ye. Leshchenko, R.M. Morozova, L.V. Nosokin, A.N. Frolov. Problems in Space Biology, Vol. 7, p. 307, 1967.

In animals repeatedly exposed to the brief (0.6 and 3.5 sec) action of wide-band noise with an intensity of more than 126 dB hemorrhages up to 3 mm in diameter were found in the lungs at necropsy. Microscopic examination of pieces of lung tissue with hemorrhages showed rupture of capillaries and larger vessels. The appearance of hemorrhages was preceded by emphysema of the marginal areas of lung tissue, which spread to the lateral surfaces of the lungs in the case of exposure to noise with an intensity exceeding 130-135 dB, giving them a nodular appearance. Figs. 4. Refs. 7.

Effect of Sound on Adrenocortical and Thyroid Function and Higher Nervous Activity of Albino Rats. T.S. Barutkina, T.T. Zarubaylo, M.I. Mityushov, A.N. Panov, V.V. Rakitskaya, Ye.V. Sokolova. Problems in Space Biology, Vol. 7, p. 310, 1967.

Sound of comparatively low intensity (70 dB, pitch 650 Hz), when applied for a long time, causes increased adrenal and thyroid function and slight changes in higher nervous activity. All the changes in the functions which were studied, arising under the influence of acoustic stimulation, were transient, and this can be attributed to adaptation of the body to the action of the stimulus. Tables 3. Fig. 1. Refs. 18.

Effect of Hypodynamia on Nitrogen Metabolism and Importance of Graded Physical Exercises for Maintenance of the Nitrogen Balance. Yu. K. Syzrantsev. Problems in Space Biology, Vol. 7, p. 317, 1967.

A marked negative nitrogen balance is observed in a state of hypodynamia (strict confinement to bed, immersion in water). When human subjects are kept in small rooms the nitrogen excretion in the urine is increased by 14%. The increased nitrogen excretion is evidence of a decrease in protein resynthesis and of some degree of atrophy of muscle tissue, an unfavorable factor when the need arises for a change from hypodynamia to active muscular work. Physical exercises, with an energy cost of 400 kcal, restores the nitrogen balance. Tables 2. Refs. 19.

Effect of Qualitative Differences in Diet on Metabolism in Hypodynamia. Yu. F. Udalov, R.V. Kudrova, M.I. Kuznetsov, P.P. Lobzin, V.A. Petrovykh, I.G. Popov, I.A. Romanova, Yu.K. Syzrantsev, A.M. Terpilovskiy, L.N. Rogatina, N.A. Chelnokova. Problems in Space Biology, Vol. 7, p. 323, 1967.

Metabolism (nitrogen, carbohydrate, lipid, mineral, vitamin) and energy were studied under conditions of restricted mobility in subjects receiving two

diets with different contents of food substances (diet 1: 120 g protein of which 101 g was animal, fat 101.2 g, carbohydrates 297.2 g, total calorific value 2653 kcal; diet 2: 57.4 g protein, of which 56.6 g was animal, fat 67.1 g, carbohydrates 266 g, total calorific value 1951 kcal) for 7 days. The changes in metabolism were less marked when diet 2 was given; the negative nitrogen balance was small, excretion of free amino acids in the urine was not increased by comparison with the period of unrestricted movement, and the protein assimilation was unchanged during hypodynamia. Diet 2 can be recommended for use under hypodynamic conditions. Tables 3. Refs. 6.

Nutritional State of Human Subjects Kept for Long Periods in a Horizontal Position and Subsequently Exposed to Accelerations. V.A. Petrovykh, R.V. Kudrova, M.I. Kuznetsov, P.P. Lobzin, I.G. Popov, I.A. Romanova, Yu.F. Udalov, N.A. Chelnokova. Problems in Space Biology, Vol. 7, p. 330, 1967.

Some aspects of the feeding of subjects under hypodynamic conditions preceding exposure to overloads were studied in healthy persons for 10 and 15 days. The diet during hypodynamia was: protein 125 g, fats 105 g, carbohydrates 307 g, calorific value 2745 kcal.

No significant changes took place in enzyme function of the gastric glands. Excretion of urea, ammonia, amino acids, and uric acid in the urine was increased. The basal metabolism was slightly lowered. Indices of lipid metabolism (total lipids, cholesterol, lipid phosphorus, acetone in the urine) and also the blood sugar were within normal limits. Some indices of acid-base balance (titratable acidity of the urine, pH) remained within normal limits. Excretion of calcium and phosphorus in the urine was increased. The supply of vitamins B₁, B₂ and B₆ was lowered. The diet studied was on the whole adequate in food value and content of the principle food substances for subjects under conditions of hypodynamia followed by exposure to overloads. Tables 8. Refs. 8.

Use of a Biomass of Unicellular Algae for Human Consumption. Yu. I. Kondrat'yev. V.P. Bychkov, A.S. Ushakov, Ye.Ya. Shepelev. Problems in Space Biology, Vol. 7, p. 338, 1967.

Three investigations were carried out in which the diet of 12 volunteers included 50, 100, and 150 g dry biomass of unicellular algae for 20-23 days. In the first investigation 3 subjects were used, 4 in the second, and 5 in the third. No abnormality in the state of health of the subjects was found in the first two investigations. In the third, edema and petechial hemorrhages of the skin of the face, fingers, and toes of the right foot were observed. They developed at different times and differed in severity in different subjects, being absent in only one. These manifestations are evidently allergic in nature. Refs. 15.

Mathematical Method for Calculating Necessary Quantity of Products for a Given Diet Using a Limited Assortment of Products. M.F. Fomin. Problems in Space Biology, Vol. 7, p. 344, 1967.

A method of calculating the quantities of individual products in the diet taken from a given assortment and yielding a stipulated calorific value, and observing stimulated ratios between the various products is discussed. Two ex-

amples of theoretical calculations of diets with stipulated ratios between proteins, fats and carbohydrates, and a stipulated calorific value, made up from a limited range of products, are given. Tables 3.

Heterotrophic Organisms as a Source for Human Consumption During Long Spaceflights.

V.I. Yazdovskiy, G.S. Ratner. Problems in Space Biology, Vol. 7, p. 356, 1967.

Several heterotrophic organisms are analyzed from the point of view of their inclusion in a closed ecological system. In the authors' opinion, organisms from the class of the lower crustaceans (genera *Daphnia*, *Gammarus*), fishes (*Tilapia mossambica*) and birds are promising. As primary utilizers of organic matter, preference is given to activated sludge. Fig. 1. Refs. 13.

Water Supply for the Crew During Spaceflights. A.A. Moiseyev, Yu.S. Koloskova, Yu.Ye. Sinyak, S.V. Chizhov. Problems in Space Biology, Vol. 7, p. 362, 1967.

Some aspects of the water supply for crew members of spacecraft are examined. Experimental data concerned with the further development of freeze-drying and catalytic-oxidation methods suggested previously by the authors for regenerating water from moisture-containing human metabolic products are presented. It is shown that water regenerated by these methods can be used for drinking purposes. Tables 3. Figs. 2. Refs. 23.

Possible Use of Water Condensed From a Viable Cabin Atmosphere for Drinking and Other Dietary Purposes. V.S. Khalturin, Ye.Ya. Shepelev, V.A. Kryuchkov, N.A. Gaydamakin. Problems in Space Biology, Vol. 7, p. 373, 1967.

Results of a toxicologic investigation of the condensate of atmospheric water vapor of an airtight cabin, used by human subjects for long periods of stay, are described. The condensate may contain certain impurities having a harmful effect on the human body. After purification by adsorbents, the condensate is fit for use as drinking water. Table 1. Refs. 5.

Ways and Means of Reducing to a Minimum Microflora in Small Rooms Intended for Long-Term Experiments with Subjects. V.I. Vashkov, Ye.N. Nikiforova, N.V. Ramkova, R.V. Adamov. Problems in Space Biology, Vol. 7, p. 381, 1967.

A method of reducing microflora in small rooms is suggested. The bacterial population is reduced by applying a group of measures including disinfection of the room itself, treatment of soft articles, preparation of the subjects for the experiments, and precautionary measures for communication between subjects and experimenters.

Investigation of the State of the Human Skin After Prolonged Restriction on Washing. I.G. Popov, V.V. Borshchenko, F.K. Savinich, M.I. Kozar', A.M. Finogenov. Problems in Space Biology, Vol. 7, p. 386, 1967.

Contamination and the condition of the skin and of the clothing materials of persons spending up to 60 days in closed rooms without special toilet of the skin covered by clothing were studied. The degree of contamination of skin and clothing by products of the cutaneous glands was judged from accumula-

tion of chlorides and organic substances. The mean contamination of clothing and skin per diem varied from 117 to 403 mg chlorine. Clothing absorbed about 90% of the chlorides and 80% of the organic substances. The pH moved toward the acid side. The level of bacterial contamination became stabilized in the 3rd week. The bactericidal index of the skin fell to 60-70. Skin diseases were of the usual kind and did not interfere with work. Rational choice of hygienic parameters of the living environment can substantially reduce contamination of astronauts' skin and clothing and also reduce the frequency of hygienic treatment of the skin. The scalp, face, fingers, perineum and feet must be cleansed more often than other parts of the body. Tables 3.

Astronauts' Basic Requirements of Personal Hygiene Materials. V.V. Levashov, A.M. Finogenov. Problems in Space Biology, Vol. 7, p. 393, 1967.

Data are described showing the dynamics of human skin contamination during prolonged isolation. The connection between the chemical composition of the contaminants and the bacterial population of the skin surface is examined. On the basis of the results of long-term experiments, general medical and technical requirements relative to personal hygiene articles are specified.

Objective Evaluation of Deodorizing and Freshening Action of Oral Hygiene Preparations under Specific Conditions. Yu. A. Fedorov. Problems in Space Biology, Vol. 7, p. 397, 1967.

Possible causes of odors from the mouth and ways of their prevention are discussed. A combined method of study of various constituents of the mouth fluids is suggested for the objective evaluation of the deodorizing action of oral hygiene preparations. Refs. 7.

Toxic Gaseous Substances Liberated from Human Feces during Storage. V.V. Kustov, V. I. Mikhaylov, L.T. Poddubnaya, L.N. Rogatina. Problems in Space Biology, Vol. 7, p. 400, 1967.

The principal gaseous toxic substances liberated during storage of human feces for 5 days were determined. Feces are a source of liberation of large amounts of ammonia and its compounds, hydrocarbons, fatty acids, phenols, oxides of nitrogen, carbon monoxide, hydrogen sulfide, indole, and other toxic substances into the surrounding medium. If feces are preserved with copper salt V the liberation of ammonia and oxides of nitrogen is greatly reduced (by 4 and 10 times respectively) and that of carbon monoxide increased 10 times. It is suggested that the liberation of toxic substances from feces can be reduced if the preservative inhibits not only the microflora, but also oxidative processes. Tables 2. Refs. 7.

Toxic Gaseous Substances Liberated from Urine During Storage. V.V. Kustov, V. I. Mikhaylov, L. T. Poddubnaya. Problems in Space Biology, Vol. 7, p. 405, 1967.

Fresh urine and urine preserved in closed containers can be a potential source of pollution of the atmosphere of pressurized cabins with ammonia, aliphatic amines, phenols, mercaptans, hydrogen sulfide, fatty acids, carbon monoxide, and hydrocarbons. Tables 2. Refs. 6.

Search for Preparations for Feces Preservative Useable Under Spaceflight Conditions. L.N. Rogatina. Problems in Space Biology, Vol. 7, p. 408, 1967.

Of 24 preparations studied as preservatives of feces, 5 from the group of salts of heavy metals were chosen. In their efficacy they can be arranged in the following order: copper salt B, silver nitrate, silver sulfate, silver fluoride, copper sulfate. Table 1. Refs. 3.

Medical Provision for Long Space Flights. G.L. Yaroshenko, V.G. Terent'yev, V.A. Chichkin. Problems in Space Biology, Vol. 7, p. 412, 1967.

In space flights the weight and dimensions of equipment in the spacecraft are limited. This applies also to medical supplies. The minimum level of medical supplies can be determined if the probable morbidity among the astronauts can be predicted. Diseases and disorders encountered among people taking part in long-term experiments or working under extreme conditions can serve as guidance for prediction. A method of calculating the statistical probability of illnesses during long space flights is suggested and the conclusions obtainable from its use are discussed. Table 1. Refs. 1.

Physiological Aspects of the Use of Hypothermia in Space Medicine. P.V. Vasil'yev, G.D. Glod. Problems in Space Biology, Vol. 7, p. 416, 1967.

Experimental data from a comparative physiological analysis of different methods of blocking protective and adaptive reactions during external air cooling of dogs and albino rats are described. The possible physiological mechanisms of the disturbance of homeostasis in a state of reversible, prolonged artificial hypothermia are examined. Some promising ways in which effective methods of blocking the thermoregulatory mechanism in animals may be sought are outlined. The aims of artificial hypothermia in long space flights are enunciated and some essentials of methods used to produce it are stated. Table 1. Refs. 47.

Results of Physiological and Ecological Investigations of Chlorella Cultures as a Link in a Closed Ecological System. Ye.Ya. Shepelev, G.I. Meleshko. Problems in Space Biology, Vol. 7, p. 423, 1967.

A brief survey of the results of combined investigations of a Chlorella culture as the possible basis for construction of photosynthetic reactors or as one of the links of a closed ecological system is given. Data showing the principal conditions for highly productive cultivation of algae are presented (balance of mineral food elements in the nutrient medium and cells, gas exchange of the culture, mineral and biochemical composition of biomass, etc.). The principal results of an investigation of the dynamic characteristics of algal suspensions for spontaneous and photodependent fluctuations in productivity are also given. Tables 3. Fig. 1. Refs. 24.

Biotechnical System of Automatic Control of Photosynthesis. M.A. Khvedelidze, S.I. Dumbadze, V.G. Apridonidze, I.S. Zaalishvili, T.L. Khomeriki, Kh. G.Gagua, M.Sh. Lomsadze, B.T. Zhorzholiani. Problems in Space Biology, Vol. 7, p. 432, 1967.

In a biotechnical system "Chlorella suspension—source of light" a feedback is used to regulate the periods of light and darkness applied to the Chlorella suspension, based on the magnitude of the photoelectrochemical current. Discrete automatic control over the luminous flux and recording of the "light—darkness" period are carried out by means of a type N-373 automatic writer, modified for the purpose and included in an amperometric circuit for measuring intensity of O_2 output during photosynthesis. An optoelectrical automation system is added inside the instrument. Preliminary results of investigation of such a biotechnical system are described. Figs. 5. Refs. 17.

Study of Photosynthesis of Chlorella Grown under Constant Conditions. I. V. Aleksandrova, Ye. A. Ivanov. Problems in Space Biology, Vol. 7, p. 441, 1967.

Experimental data obtained with an apparatus for cultivation of Chlorella under stable conditions of growth showed that the probability of appearance of spontaneous changes in intensity of photosynthesis is 0.18. The mean value of deviations of photosynthesis is 21%. Changes take place at the rate of 6-7%/hour. It is concluded that continuous control of photosynthesis can be replaced by intermittent. Table 1. Figs. 5. Refs. 3.

Effect of Some Gaseous Contaminants in the Atmosphere on Photosynthetic Activity of Chlorella. M.N. Korotayev, V. V. Kustov, G.I. Meleshko, V.I. Mikhaylov, Ye. Ya. Shepelev. Problems in Space Biology, Vol. 7, p. 447, 1967.

The effect of certain gaseous contaminants of the living atmosphere on the photosynthetic activity of Chlorella was studied. It was found that during the isolated action of low concentration of ammonia, carbon monoxide and acetone the mean CO_2 assimilation by the algal cells increased, whereas under the influence of hydrogen sulfide and human expired air it was decreased. Tables 5. Refs. 5.

Characteristics of Growth and Gas Exchange of the Alga Anacystis Nidulans in Intensive Culture. T.B. Galkina, I.I. Kashkovskiy, O.A. Kurapova, Ye.K. Lebedeva, G.I. Meleshko, Yu. N. Ul'yanin. Problems in Space Biology, Vol. 7, p. 453, 1967.

Experimental data for the rate of growth of the biomass, CO_2 assimilation and oxygen liberation, pH dynamics, and pattern of nitrogen extraction from the medium by algae Anacystis nidulans in intensive accumulative culture are given. The coefficient of assimilation and chemical composition of the biomass were investigated and found to be close to those of Chlorella. The specific photosynthetic productivity of the culture of A. nidulans under intensive conditions is similar to the productivity of the Chlorella culture. Tables 3. Figs. 3. Refs. 12.

Choice of Animal Components of Closed Ecological Systems. N.V. Mironova. Problems in Space Biology, Vol. 7, p. 459, 1967.

The paper describes an attempt to analyze the possibility of using Tilapia mossambica Peters for this purpose as an aquatic variant of a closed ecological system. The results of the investigation show that tilapias are tolerant to the conditions of existence, can exist in high stocking density, can utilize a wide range of both animal and plant foods. They reproduce frequently, look after their young, and the survival rate of the young is high, indicating the possibility of a rapid increase in population. The comparatively rapid rate of growth suggests that a high rate of increase of total biomass can be expected. Tables 8. Refs. 32.

Effect of Food Supply on Growth of Tilapia (Tilapia Mossambica Peters). N.V. Mironova and T.A. Skvortsova. Problems in Space Biology, Vol. 7, p. 471, 1967.

Tilapias can utilize the green mass of higher plants from 2 to 7 months of age. They can live and grow when fed for a long period (up to 5 months in the experiments) on a purely plant diet, even if it consists of plants of only one species. A small addition by weight of animal food considerably increases the rate of growth of the fish compared with that of fish receiving a purely vegetable diet. Tables 7. Fig. 1.

Comparison of Growth of Tilapias (Tilapia Mossambica Peters) when Fed on Chlorella and Other Foodstuffs. N.V. Mironova. Problems in Space Biology, Vol. 7, p. 478, 1967.

Chlorella is considered to be a first-class, balanced food for growth of tilapias. In mean weight and utilization of food for growth the fish very closely resemble tilapias receiving animal food and give the highest growth indices, by contrast with fish receiving only higher plants. Tables 7. Refs. 3.

Effect of Vibration and Linear Accelerations on Fish. V. Ya. Mamontov, G.B. Mel'nikov. Problems in Space Biology, Vol. 7, p. 485, 1967.

Vibrations of different frequencies, but with equal vibro-overloads (about 10 units) and equal exposure time (6 min) produce effects of different intensity on fish. Frequencies of 80-90 Hz had the strongest action, sometimes lethal, on fish weighing from 40 to 130 g and measuring from 16 to 21 cm in length. The existence of resonance effects for this frequency band and for fish of this size is postulated. Tables 1. Figs. 5. Refs. 4.

Action of γ -Rays and Protons on Chlorella. I.D. Anikeyeva, E.N. Vaulina, V.A. Shevchenko. Problems in Space Biology, Vol. 7, p. 493, 1967.

Survival and mutation rates of the unicellular alga Chlorella strain LARG-1 as a function of dose were studied during exposure to Co^{60} γ -rays and 660 MeV protons. The relative biological effect for protons is 7.2 krad and for γ -rays 11.5 krad (1.6:1 in favor of protons). The number of visible mutations increases proportionally to the dose of protons and γ -rays. γ -Rays give 7.8% of mutations and protons 3.7%, indicating the high mutagenic effect of γ -rays relative to their lethal action. Table 1. Figs. 2. Refs. 7.

Study of Regeneration of Air and Water by Higher Plants in a Closed Space.
N.T. Nilovskaya, M.M. Bokovaya. Problems in Space Biology, Vol. 7,
p. 496, 1967.

Carbon dioxide assimilation by most of the experimental plants (Chinese and ordinary cabbage, potato, beans, radish) varies between 50 and 60 g/m² area sown/day. Highest intensity of CO₂ assimilation is given by beetroot, sugarbeet and soybean (102-152 g/m² area sown/day). Assimilation of CO₂ by the crops fluctuates during the 24-hour period. Between 12 noon and 3 P.M. depression of CO₂ assimilation is observed. During the period of darkness the plants excrete 3-8.5 g CO₂ per square meter sown area, or 4-7% of the daytime CO₂ assimilation. The intensity of transpiration of the plants under the experimental conditions is 19-40 g/m² of leaf surface, giving a yield of 1.5-2.5 liters water/m² leaf area. Tables 4. Figs. 5. Refs. 14.

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PROBLEMS OF SPACE BIOLOGY, Vol. 7

ANNOTATION

Three problems are examined in this collection: psychophysiological aspects of operational activity, questions relating to the habitability and hygiene of spaceship cabins, and also the problem of biotechnology.

This publication is intended for a broad circle of biologists, physicians, physicists, chemists and designers.

FOREWORD

Space science is continuing its rapid, successful development, enriching the general fund of human knowledge with new achievements which are often startling because of their novelty and significance. /3*

Also continuing to grow is the number of scientific publications. The necessity of timely, operational information of specialists has led to the appearance in our country in 1967 of a new scientific journal "Space Biology and Medicine."

The contributors to and readers of the collections entitled "Problems of Space Biology" undoubtedly join in the congratulations and best wishes of success sent with a feeling of great satisfaction by the editorial staff of the "collections" to the editorial board of the new journal and its editor-in-chief, Academician V. V. Parin.

Scientific publications are important not only because they reveal the results and prospects of research. Of no less importance is the historical aspect. A glance at the history of science shows clearly that it is replete with examples of genuine heroism and selfless service to humanity.

To our great regret, it also contains quite a few tragic pages in connection with the achievement of new goals by researchers, with penetration into new and mysterious fields.

As the events of this year have shown, space science is no exception. In January, 1967, the American astronauts Grissom, White and Chaffey perished at Cape Kennedy while testing a new spacecraft, the "Apollo."

In April, 1967, the outstanding cosmonaut and researcher, Engr.-Col. V. M. Komarov, twice recipient of the award "Hero of the Soviet Union," perished tragically while carrying out a test flight of the new Soviet spacecraft "Soyuz-1."

These tragic events have deeply troubled the public all over the world; they have been the source of numerous comments, once again emphasizing the exceptionally important significance of further improving ways and means intended to ensure flight safety.

Space medicine and biology are being called upon to play an important role in the development. /4

* Numbers in the margin indicate pagination in the foreign text.

Continuing the general plan by which Vol. VI was put together, the articles of Vol. VII have been grouped under three main problems, namely, psychophysiological aspects of operational activity, questions relating to the habitability and hygiene of spacecraft cabins, and also problems of biotechnology.

The editorial board hopes that the readers will receive the articles with interest; the board will also be grateful for critical remarks and suggestions which it will attempt to take into account when putting together subsequent volumes of the collection.

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Problems of the Reliability of Man in Spacecraft
Control Systems*

P. K. Isakov, V. A. Popov and M. M. Sil'vestrov

Man or automatic devices in the investigation of space, this is the problem that has long been discussed in the press. At the present time an even larger number of researchers is approaching a unique solution of this problem. The solution consists in a judicious combination of the properties inherent in man and automated systems.

The inclusion of a human being in a spacecraft control system increases its reliability and in some cases reduces the weight and bulk of the equipment. Moreover, in order to ensure the operational reliability of pilotless spacecraft it is necessary to incorporate a high level of equipment redundancy, that is, to provide for a multiple reserve of systems and instruments. But if the work of an operator is combined with only a single or double reserve, it is almost certain that systems of the craft will function without failure for a considerable period [4]. But if the operator is also provided with the means to repair the faulty parts of the control system, the reliability will become very high, being governed essentially by the reliability of the operator. A method in which the reliability of spacecraft control systems is enhanced by rational combination of the functional capabilities of man and the characteristics of the equipment is considerably more effective than any purely technical method of ensuring reliability.

The "operator-spacecraft" system is a closed multiloop system. In such a system an operator can fulfill the role of the logic and computer devices, of the meter of the control process parameters, of the amplifying, integrating, and differentiating links, of the control formulation system, etc. /6

The amount of information presently available on the operational characteristics of an astronaut controlling a spacecraft and the research instrumentation during actual space flights is still insufficient. As is to be expected, however, the experimental characteristics of various work operations performed by astronauts in flight are often very different from those on earth.

For instance, the time spent by cosmonaut B. B. Yegorov to perform operations with the medical equipment in the "Voskhod" was 1.5 to 2 times greater than he spent on earth. Without doubt, this was a result of specific space-flight conditions affecting the cosmonaut-operator.

Because the amount of information obtained during flight in space is insufficient, it is especially necessary to make wide use of ground test equipment. At the same time, investigation of the reliability and efficiency characteristics of human operation in test devices on the ground, both from the standpoint of principle and of actual conditions, requires that "man-machine" models be set up so that not only the control process itself can be simulated, but also the specific conditions that contribute to creating any given state of a human operator.

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Let us mention the basic problems that can be solved by means of such simulations.

1. Analysis of the dynamics of the control process of a system in which a man participates. In such a study the given equations of the plant and control system are solved on computers in a natural time scale.

2. Solution of the problem of synthesis of the control system. This problem reduces to choosing the structure of the variable part of the system, its characteristics, the values of the parameters, and the rational form of the information model, on the basis of the given technical conditions and of the known properties of the operator.

3. Experimental investigation of the system decided on. In such investigations some of the system elements are actual ones, along with their properties; the operation of the rest of the elements is reproduced by a computer in a natural time scale according to the given equations.

4. The experimental study of the response of the system under laboratory conditions, and of its efficiency, when the operator is subjected to simulated specific flight factors (overwork, hypodynamia, isolation, noise, vibration, ambient gaseous medium, illumination, etc.).

5. Formulation of the qualities of the operator in accordance with the requirements of the control system. This problem is solved by training operators on simulators and special trainers as well as by using special drug-induced effects.

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The control process is simulated with the aid of a computer. An analog-digital complex is used to solve complicated problems. Signals are fed from the output of the simulator to an information model, that is, to an indicator and signaling system. Specific flight factors can be simulated by means of dynamic test arrangements which imitate the external flight conditions, the life-support systems, and also by means of special devices which make it possible to elicit in the organism reactions which are similar to the reactions of the organism to the flight factors being applied.

The system is designed to record the variables of the control process, the responses of the operator, and his physiological functions. The efficiency and reliability of a control system in which the human participates is evaluated by analyzing the indications from the dynamics of the control process, errors in the steady-state and forced modes, the final result of the control, the energy expended in the control process, the quantity and nature of the incorrect actions of the operator, and changes in the physiological functions of the operator.

The psychophysiological features of human activity in controlling a spacecraft and its equipment depend to a significant degree on the systems with which he is working. In space flight it is necessary to perform control operations both with a time deficit and a time surplus. A surplus of time is the reserve of time available to the operator in performing a certain task; it is considerably greater than the total time required to carry out the operations associated with the completion of the task. A time surplus may be available for controlling the angular motions of the craft, which can be done either by active or passive means. The force moments generated by the ambient medium are used in passive stabilization of the spin of a space ship. The force moments arising as a result of interaction between the craft and the ambient medium are small, and therefore the spin period

will be large, from a few tens of minutes (when using the gravity and magnetic field gradient of the earth or the aerodynamic forces of orbital flight) to several hours (when using the radiation pressure of the sun). If active means are used (jet engines, interior rotating masses, etc.), the spin rate increases, but in order to economize on power reserves, it remains about several degrees per second, and the time of the transient process may be of the order of several minutes. In this case there is also a surplus of time. But when the spacecraft is carrying out such flight steps as approach and docking, reentry into dense atmospheric layers, touchdown, etc., the astronaut has to work under a time deficit situation. Time deficit and information overload may cause sharp deviations in the activity of an operator, reducing operational reliability. The primary events under such conditions are gaps in incoming signals and delayed response to the increasingly complex situation. When information arrives too slowly and the control processes take too much time (surplus of time), the human operator begins to be distracted from controlling the given process, and this may lead to incorrect actions and deterioration of the control process. Surplus of time and a monotonous situation lower the functional level of the human analyzer systems. Experimental study of operational activities has shown that in normal flight of "Vostok" the cosmonaut works with the instrument package without a time deficit. The instrument reading time does not limit the execution of operations in any case. /8

From 2.2 to 3.1 sec are required, while controlling the spacecraft, to determine the numerical value of one of the parameters characterizing the environmental state of the cabin (the temperature, oxygen content, carbon-monoxide gas, etc.). This period depends on the form of the face of the instrument and on its location on the instrument panel. The mean time required to perceive light signals fluctuates between 0.8 to 1.2 sec, depending on the color and intensity of the signal and its location on the signal panel [1]. The accuracy of manual control depends on the information model, on the location of the image of the parameters being read relative to the eyes of the operator, and on the indication systems within the operator's field of view. The accuracy of control by a reference point is greater when the deviation of the point is determined relative to a vertical reading line rather than to a horizontal one. This was observed in control experiments on a simulator when the operator had to carry out the following operations: place one circle concentric to another, keep a luminous dot or a symmetrical figure in the cross-lines on an electron-beam tube, keep a cross symmetrical when the two lines forming the cross were movable relative to each other, so as to correspond with the control dynamics, and also when reading the indications of instruments with vertical and horizontal scales. For example, the accuracy of mounting a circle on a vertical control channel was less by a factor of 1.6 than on a lateral channel. The accuracy of controlling the location of a spot on the screen of an electron-beam tube in conformity with the spin dynamics of a spaceship in a vertical control channel (in the axial plane) was less than in a lateral control channel by a factor of 2. The accuracy with which the cross bars were kept symmetrical during manual control of the spin stabilization of a spacecraft was better in the vertical case by a factor of 2.2 than in the lateral case. Of definite interest is the study of the time required to perceive signals indicating the magnitude and rate of mismatch in the control process when using an electron-tube indicator. The experiments showed that when the luminous spot deviated from the cross-hairs of the indicator by more than 4 mm, the average time it /9

took to determine the error was 0.9 sec; when it deviated by 1 mm, the time of perception was 1.2 sec. When the speed of motion of the image was more than 1 mm per sec, the time required to determine the sign of the derivative of the deviation was about 1 sec and was almost independent of the speed. At a lower speed the average time it took to determine the sign of the mismatch derivative increases, reaching 4.2 sec at a speed of 0.1 mm per sec.

As the tasks of space flight become more complex, a piloted spacecraft will become saturated with an even greater number of indicators, signal devices and control units. The nature of space flight, the fact that it takes place in phases, make it absolutely necessary that the astronaut receive information from all or from a majority of the instruments and signal devices, and that not all the control levers be necessary in every given step. The operational reliability of the operator in spacecraft systems increases if we employ the principle whereby the operator need handle the various indicators, signal devices and control units only step by step, in accordance with the tasks to be performed.

The particular features of space flight conditions, such as weightlessness, considerable overwork during launch and descent, intermittent time deficits and time surpluses in performing operational tasks, the fact that the flight is carried out in phases, the multiple sources of information in the control system, all these factors determine how we must construct the information model and the control consoles, the scientific research equipment, and the operational instruments. In the case of spacecraft flight of a team consisting of several men, the reliability of the "man-spacecraft" system depends to a considerable degree on how the control functions are distributed among the crew members. For example, experiments have shown that if the functions of controlling eight specific points of the process are rationally distributed between two operators, the quality of control improves by a factor of 2.5 as compared with control by a single operator, and the percentage of unsuccessful control actions decreases by one half.

As indicated above, the reliability of the man-spacecraft system can be studied in an appropriate manner if various factors (noise) act on the operator.

In doing so, we should strive to have the state of the operator approximate as closely as possible the state that may be observed under normal and extreme flight conditions. Let us indicate several examples of the nature of such noise effects.

While working in the simulator the operator was presented with experimental illusions of rolling. This was done by exciting the vestibular analyzer with direct current (from 2 to 5 milliamps). During the period the rolling illusion was effective, the time it took to perceive the signals of the paravision indicators increased by 2 to 3 seconds. Also noted was a characteristic interruption of coordination of control motion.

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When the model cabin was subjected to noise of up to 90 db and a temperature of 40—45° C, pronounced changes in the quality of control were noted only after the operator had been subjected continuously to 3 to 4 hours of these conditions. In particular, the three-dimensional control of the spacecraft (in the simulator) deteriorated by a factor of 1.2.

A study of the effect of prolonged isolation and hypokinesia on the activity of an operator in transmitting information by means of a teletype instrument [2] and in controlling the altitude of a spaceship showed that pronounced deterioration of

the efficiency was noted in the first few days of isolation and hypokinesia. The quality of orientation became worse by a factor of 1.5 as compared with the initial compared data. On the third day the quality of operation was restored almost to the original level. It should be emphasized that an analogous tendency was observed in actual tendency flight.

The operational reliability of a human is also determined by the way in which he handles his work under complex conditions, e.g., when the operator must control the operation of various systems, answer transmitted inquiries, etc., while performing the main task of control. In this case psychological noise of peculiar nature occurs, causing the most significant failures in the quality of control. In the experiments the operator was presented with an additional task in which he was to turn away from his control functions in order to read instrument indications, to count light signals, etc. The necessity of switching tasks and distributing his attention resulted in deterioration of the quality of three-dimensional control of the motion of the plant according to an instruction device by a factor of 1.6 to 1.8, and the time required to perceive paravisual indicators increased from 2-3 to 8-10 sec [3].

When an operator had to control eight distinct parts of the control process while being interrogated by radio on the readings of indicators and signal devices, the quality of manual three-dimensional control of spacecraft motion deteriorated by a factor of 1.7 as compared with control in the absence of noise.

The above presentation indicates that an effective approach to estimating human reliability in spacecraft control systems consists in the broad use of simulators of the dynamics of the control process and of the state of the operator, approximating as close as possible his state under normal and extreme flight conditions.

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SOME ASPECTS OF THE ACTIVITY OF SENSORY SYSTEMS
AS APPLIED TO PROBLEMS OF SPACE PHYSIOLOGY*

V. D. Glezer, V. A. Kislyakov, V. A. Kozhevnikov,
V. N. Chernigovskiy and L. A. Chistovich

There is no doubt that the normal functioning of sensory systems is one of the most important conditions ensuring effective adaptation to the environmental situation in general and, in particular, to the complex medium of a spacecraft.

In view of such special conditions, the problem of the mutual operation of man and automatic equipment, i. e., the "man-machine" problem, takes on special significance.

Astronauts who are, in effect, almost completely freed from performing physical labor must solve spacecraft control problems, make various observations, and also make responsible decisions rapidly and without error.

All these problems are connected with the acquisition and processing of specific information, the most important task being the effective coding of this information and correlation of the characteristics of machines with the "capacity" of the astronaut-operator.

In conformity with this general problem, the present report is devoted to an examination of several important aspects of the problem of acquiring and processing information and of recognizing sensory images.

Of course, these aspects will not in any case exhaust the entire problem. However, we have preferred to address ourselves specifically to these aspects because we have had certain experience in studying them.

The first aspect to be considered relates to the problem of orientation in space and was studied in experiments with animals (V. A. Kislyakov et al.). The second relates to the problem of recognizing visual images (V. D. Glezer et al.) and, finally, the third relates to the problem of recognizing speech sounds (V. A. Kozhevnikov, L. A. Chistovich et al.).

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The second and third themes are based on data obtained from observations of human beings.

The proposed solutions to the problems are not considered to be definitive and are subject to subsequent, more accurate definition.

First, let us dwell on the characteristics of the scheme we chose as the initial scheme in solving the problems we have taken up.

We should take as an accepted fact that the problem of a more rational distribution of functions among the astronaut and the equipment cannot be solved empirically or on the basis only of common-sense ideas, but requires a thorough

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theoretical elaboration by the methods of engineering psychology. In recent years a rather considerable volume of experimental data characterizing specific parameters of the human operator has been accumulated. However, these data concern on the whole only elementary functions, such as work at a control panel, tracking a target, etc.

Not so well studied are the problems facing a spacecraft commander and a scientific observer when the volume of information to be exploited may be extremely great, while the errors committed in working out a solution may prove to be fatal. The place and role of an astronaut in the overall system of information processing and control are outlined schematically in Fig. 1.

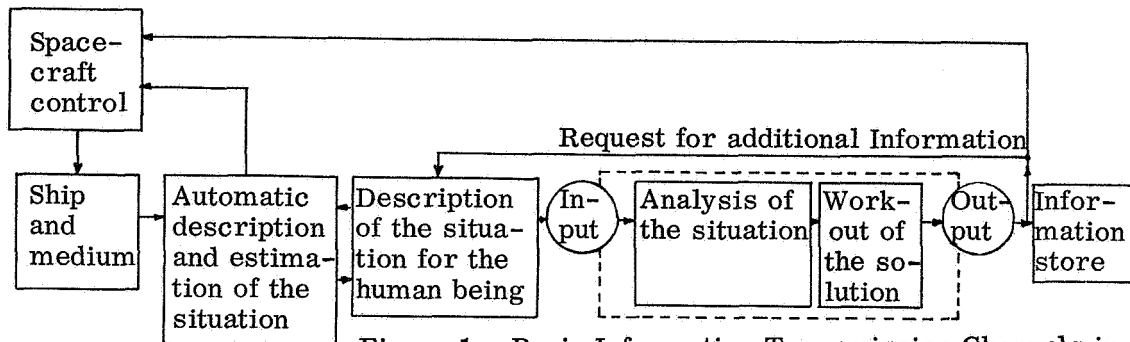


Figure 1. Basic Information Transmission Channels in a "Man-Machine" System.

The factor which is peculiar to the operational conditions of an astronaut is, first of all, that he deals not only with data from direct observation of the situation, but also with the results of automatic processing and evaluation of information, part of which has already been done by instruments. Accordingly the input information for the astronaut is represented by the signals of block N(Fig. 1), which describe the situation in symbolic and abbreviated form. Another feature of human operation is that the actions the operator takes are not the usual direct actions with machines; they are control signals which must be recognized, interpreted by the automatic control system and correlated with other signals circulating in this system.

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The most interesting aspect of engineering psychology is the choice of an optimal system of signals by which the information must be presented to the operator and the choice of an optimal system of actions by which the operator transmits the information to the instruments.

We believe it is possible to present the following principle for an overall approach to this problem.

It is obvious that the information-processing operations performed by a human being (that part of the diagram outlined by dashes in Fig. 1) are relegated entirely to the realm of thought. Although we do not know at the present time what these thought operations actually are, nevertheless we must assume that they are performed on certain signals, symbols, and categories. Logically, it must be assumed that these symbols form a certain ordered set, a thought dictionary, and that in addition there are certain specific rules for analyzing and synthesizing groups (sequences) of symbols. The dictionary and rules form together what may be called the thought language.

Having admitted a thought language, we must, of course, supplement the human information processing diagram given in Fig. 1 by at least two blocks. These are an input block, which translates the language of the signals perceived into the thought language, and an output block, which translates the thought language into a language of action.

Naturally the capacity of the system will be greater the simpler the translation from the language of the external signals to the thought language and from the thought language to the language of action. The optimum case is coincidence of languages. The literature of psychology contains the viewpoint that the thinking of a mature human being is essentially verbal; it is assumed that the thought process also includes operations on visual representations.

Considering these notions to be highly probable, we adopted the hypothesis that the optimal method of providing an operator with "input" data is to combine vocal and visual concepts. But the optimal control signals developed by the operator should be vocal commands, if possible combined with some simple motor action.

Following this scheme, we will examine all three problems successively. Whenever necessary we will be forced to curtail the purely factual part of the report, since this is governed by the lack of time. We will also be highly conservative in describing the methods used in our approach and the literature. The greatest attention will be devoted to a possible application of the results to space-flight practice.

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In the human organism two phenomena stemming from different receptor systems are characterized by general signs. These phenomena arise when the organism is subjected to acceleration or when focal points move into the field of vision of man and animals. Vestibular and optokinetic reactions are associated with these phenomena. In a high-altitude or spaceflight situation, optokinetic along with vestibular stimuli, as a result of changes in the afferent signaling of various sensory systems, are the reasons for discomfort, disruption of spatial orientation and the appearance of illusory reactions, reducing the capability of an astronaut to carry out the delicate intellectual operations of reception, analysis and transmission of information.

It is only natural that certain mechanisms responsible for the above-mentioned failures in experiments with animals must be clarified for purposes of aviation and space medicine.

It is well known that the effect of vestibular exciters in man is to produce the following illusions:

1. The illusion of counter-rotation—the apparent rotation of a body in the opposite direction after rotation has stopped.
2. The oculogyric illusion—the apparent motion of a focal point being observed when semicircular ducts are subjected to angular motion (Greybiel).
3. The oculogravitational illusion—the apparent rotation or displacement along the vertical of an observed focal point when otoliths are subjected to centrifugal forces (Greybiel).

Analogous illusory reactions can also be observed under the effects of optokinetic stimuli.

1. When a man is placed inside a large rotating, striped cylinder, he gets the sensation that his own body is rotating in the opposite direction while the rotating cylinder seems to be fixed (Kislyakov).

2. Reverse rotational illusion—this occurs when the eyes are transferred from rotating strips to fixed ones, which appear to be moving in the opposite direction (Miller).

3. Reverse postoptokinetic illusion—the apparent motion in the opposite direction of a luminous spot against a dark background after optokinetic stimulation (Miller).

4. Illusion of the fall of a luminous spot—this occurs when strips are moved vertically downward (Miller).

The illusory reactions elicited in people under laboratory conditions also occurs in real flight situations. If they take on a complex nature in flight, they lead to a lapse in spatial orientation. In connection with these facts it became necessary to have an analog of such illusory reactions in animals in order to study the nervous mechanisms responsible for their origin. Optokinetic stimulation was selected for this purpose.

In our experiments (Kislyakov et al.) we obtained a new form of nystagmus, called reverse postoptokinetic nystagmus (RPN). RPN occurs in rabbits after prolonged optokinetic stimulation and has a direction counter to the preceding optokinetic nystagmus (OKN), lasting tens of minutes (Fig. 2). The maximum RPN rhythm is observed during the first 10 to 15 minutes.

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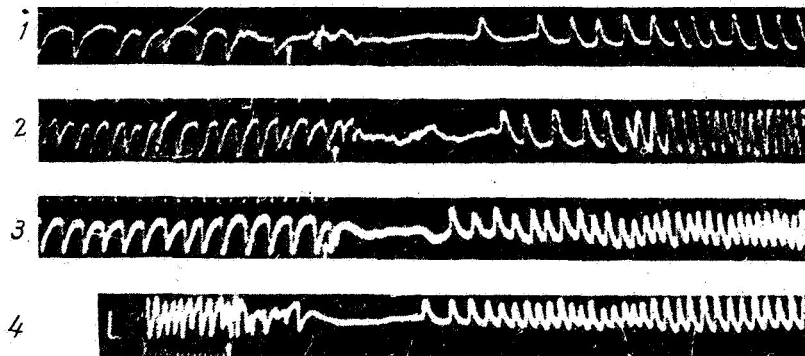


Figure 2. Electronystagmogram of OKN and RPN at the Following Rotational Speeds of the Cylinder: 1-1; 2-1.8, 3-2.5; 4-6 rpm. The Arrows Indicate the Instant the Dark Screen was Stopped; the Dots are the Marks of the Strips. The Calibration was 200 Microvolts; the Time 1 sec.

Visual exciters must be used before RPN appears (the experimental chamber must be darkened or a dark screen must be set up). Note that Miller's optokinetic illusions were more strongly pronounced when the illumination was reduced.

We consider RPN in rabbits to be an analog of illusory optokinetic reactions appearing in the form of an objective indicator-nystagmus. A change in direction of nystagmus in the case of RPN can be considered as the appearance of induction

processes in the nerve centers after the termination of OKN. Consequently, the prerequisites for the development of the opposite process are set up in the nerve centers during OKN. Special experiments in which the black-out was lifted 30 to 60 minutes after the cessation of optokinetic stimulation revealed that RPN occurs even after such a long time interval. Delayed RPN shows how long the trace excitation circulates in the nerve structures before reaching the effector—the motor neurons of the eye muscles. This forces us to assume that circulation of trace excitation takes place in the sensory and not in the motor sphere of the brain.

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On the basis of phenomenological study of RPN, in the first approximation it is possible to draw the conclusion that the cause of the illusory optokinetic reactions is trace excitation, as well as summation and induction processes in the nervous system.

These experiments indicate that traces of prior optokinetic stimulation may be stored in the central nervous system for a long period before suddenly appearing in the form of unfavorable reactions when the visual stimuli are cut back.

Optokinetic stimuli of varying frequency parameters are an indispensable companion of man in his travels on all types of modern ground, water and air transports and spacecraft.

At the same time there arises the question of the importance of the different links of the visual system in adjusting the OKN parameters to correspond with the parameters of optokinetic stimulation. From this point of view, RPN has proved to be an important index for understanding the mechanisms by which the OKN rhythm is transformed as a function of the frequency of tracking optokinetic stimuli per unit time.

Data on the frequency of OKN and RPN are given in generalized form in Fig. 3. Plotted on the ordinate axis is the frequency of OKN and RPN, characterized by the number of bursts of nystagmus per min. Each point on the graph was plotted on the basis of 20 to 40 experiments with 4 to 6 rabbits. Consequently, the dynamics of RPN frequency can be analyzed from these graphs as a function of the frequency of the preceding OKN. It is evident in the graph that the RPN rhythm reaches a maximum before the OKN rhythm does. This fact indicates that the RPN rhythm is relatively independent of the frequency of the prior OKN. At the same time the maximum RPN frequency was almost equal to the maximum OKN frequency. In essence, RPN is the appearance of prolonged cyclic activity of the nystagmic nerve centers, and its maximum frequency represents the frequency at which these centers can trigger nystagmus. This leads to the conclusion that the appearance of a plateau on the graph of the OKN frequency depended on the resolving power of the nerve centers that trigger nystagmus. On the basis of information obtained from the retina of the eye on the frequency and rate of stripe tracking, the nerve centers regulated the increase in OKN frequency within a specific range of cylinder rotation rates (1 to 6 rpm) and then maintained a stable OKN frequency (6 to 15 rpm).

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It was assumed that cessation of OKN is connected with the reaching of a critical frequency at which the flashes merge and the retina makes no discrete distinction between stripes or groups of stripes. However, the presence in our experiments of an additional index in the form of RPN permitted us to consider

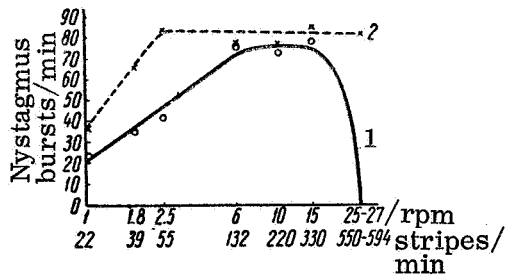


Figure 3. Change in Frequency of OKN (1) and RPN (2) at Varying Frequency of Optokinetic Stimulation.

this fact from a different viewpoint.

In fact, even in this series of experiments all the animals developed RPN after vision was cut off. This fact led to the conclusion that evidently the critical merging frequency of the moving stripes is higher for the retina and was still not reached at a speed of 25-27 rpm (550-594 stripes per min). Cessation of OKN at the given speed and frequency of stripe tracking was governed by the oculomotor apparatus for which these optokinetic stimulus parameters proved to be limiting. The eye, in making a discrete distinction between the black stripes and white intervals, did not succeed in responding to the motion of

bursts of nystagmus.

The RPN phenomenon as the appearance of automatic trace activity of the nerve centers was applied to the analysis of the mechanism of OKN frequency transformation at a different stripe tracking frequency. This made it possible to discuss the significance of the nerve centers, the oculomotor apparatus and the retina in transforming the OKN rhythm.

Now let us consider the second aspect.

The receptive fields of the retina perform a number of operations in transforming visual information: the accumulation and selection of a signal from noise, the change of sensitivity to the resolving power (that is, an increase in acuity of vision with illumination), decorrelation of signals in time and space (obtaining responses only to a change in the light signal, the selection of image contours).

At low levels of illumination the rod fields become effective, summing signals over a large area. This is achieved by high sensitivity to light, but the visual acuity is rather low. With increasing illumination, the smaller-size cone receptor fields go into action. The effective magnitude of the cone fields decreases with increasing illumination due to the development of an inhibiting process which prevents the peripheral field receptors from functioning. A diagram of the operation of the field is given in Fig. 4. At a low level of illumination a large number of receptors is connected to a single ganglion cell, all the inputs of the receptive field are positive, and excitation by the incident light is summed over a large area (Fig. 4, a). At a higher illumination level each receptor has its own separate output, the peripheral receptors transmit inhibiting signals to the output cells, and the resolution of the system is high; in contrast the sensitivity is diminished, but this is not important, since there is sufficient incident light (Fig. 4, b). During transition from one level of illumination to the next (as shown in the upper curve of Fig. 4, c), the receptive field readjusts (lower curve). At the same time a pulsed response appears, lasting until the excitation of the field is balanced by reactive inhibition. Finally, in the region where the illumination level drops, the receptive fields ensure that the contours of the image are enhanced. If the distribution of illumination over the retina is as shown in the upper curve of Fig. 4, d, the signals arriving from the receptor fields at the point of decrease in illumination level will not correspond to the true distribution; as shown in the

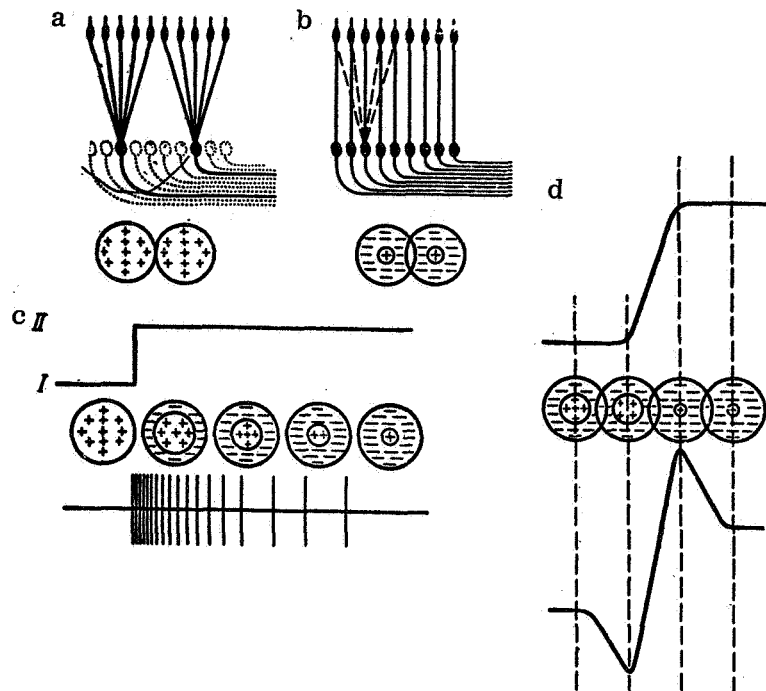


Figure 4. Diagram of the Operation of the Receptive Fields of the Retina. See the Text for Explanation.

lower curve, the drop in illumination will be accentuated. The next step in information processing is carried out by higher-order receptor fields.

The numerous data available at the present time indicate that the visual analyzer contains a number of individual channels, systems, each of which describes some particular property of the image. In the first approximation we can single out the following systems: the signal intensity coding system, the light coding system, the system for pinpointing shape elements, and the system for detecting motion. As a result, the image is a set of signals describing it in a form that is no longer the same as projected into the receptors of the retina.

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The purpose of primary information processing mechanisms is to eliminate redundancy in messages transmitted by the visual system. This redundancy is due to the statistical properties of objects of the external world and does not depend on the set of visual images which the individual has been taught. Therefore, primary information processing is carried out by deterministic mechanisms which are fixed genetically during the process of evolutionary development.

We carried out some experiments in which we succeeded in finding a psychophysiological expression for these mechanisms. In these experiments we determined the time that is necessary to recognize this or that image. The image was shown for a certain amount of time and was then replaced by another "erasing" image which completely screened out the first. Thus, after removing a plastic image, the process of information analysis was interrupted by switching the visual system over to a new problem.

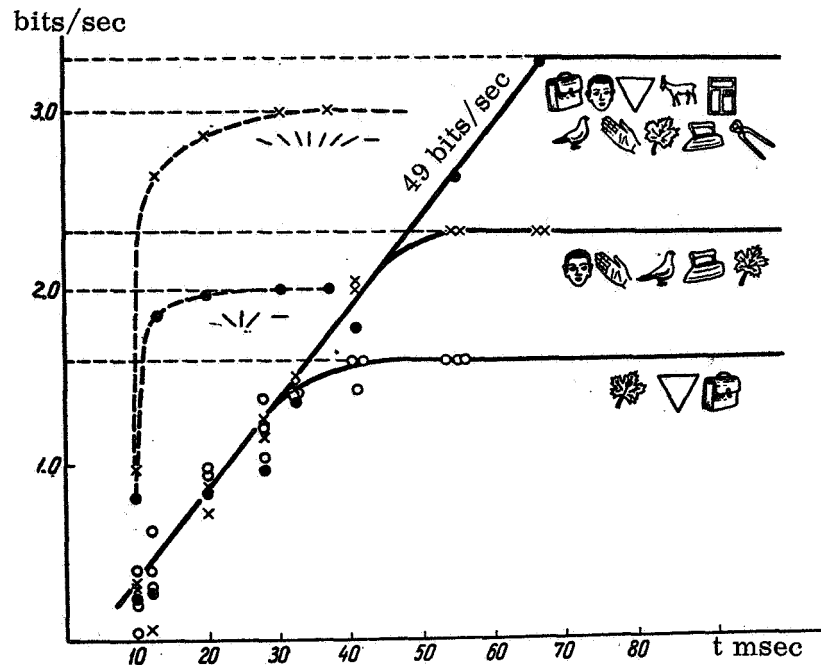


Figure 5. Quantity of Information Received by an Observer as a Function of the Information Processing Time in the Visual System when Recognizing Lines Differing in Orientation and Sketches of Objects. Size of the Image is 4° .

Shown on the axis of abscissas in Fig. 5 is the time the image was shown, and on the ordinate axis the average quantity of information obtained by an observer in one showing. The observer was trained to recognize images of a specific set. The dashes show the results of experiments in which the sets consisted of straight-line segments differing in orientation; the solid line refers to experiments in which the sets consisted of outline images of ordinary objects. The data were obtained from a test person who had been completely trained to recognize the images of a specific set.

In recognizing sets of four or eight differently oriented lines, the time of presentation does not determine the quantity of information received. The greater the choice the greater the quantity of information received by the observer at one time. This should be expected if the straight line is detected by mechanisms of the receptive field operating according to a standard program; that is, the time it takes to detect such a configuration is governed only by the signal-formation conditions. This is recognition on the basis of a fixed sample, by comparison with a stored standard. Detection of the simplest configurations of the straight-line-segment type, of specific orientation, can be considered as the singling out of elementary shape indicators.

In the recognition of sets consisting of complicated sketches, the time required for error-free detection turns out to be greater the greater the number of figures the observer may expect to be shown under the experimental conditions. This very fact that the time required for recognition changes as a function of the

magnitude of the range of possible images indicates that adjustments take place in the visual system as a result of a learning process. /21

If such images are shown for a brief period, insufficient for error-free identification, it turns out that the average amount of information received by the observer within a fixed period of time is the same for recognition of sets of three, five or ten sketches and is directly proportional to the time allowed for showing (as indicated by the solid lines in Fig. 5).

The slope of the solid line shows the amount of information received per unit time, that is, it shows the resolving power of the visual system. A calculation of the transmission power from the speed of recognition of single outline images of objects yields values of 35 to 110 bits per second in various observers (in general about 50 to 70 bits/sec).

On the basis of these and other investigations the process of visual recognition can be represented in the form of the following pattern. After primary transformation of visual information in the retina, elementary features of the image are singled out in higher regions of the visual apparatus. The mechanisms by which elementary features are singled out operate according to standard sub-programs, and therefore the time required for detection of elementary features does not depend on the quantity of information transmitted by them. The elementary features are joined together in the learning process to form complex symbols; the latter are invariant with respect to such transformations of an image as displacement within the field of vision, rotation within certain definite limits, change in dimensions, etc.

An image is recognized as a generalization by successive scrutiny the features from all sides.

What value can these investigations possibly have for problems of space biology?

Determination of the amount of information that the visual systems can process per unit time under various conditions and various parameters of the visual stimuli is necessary for rational design of equipment for the supply of visual signals (consoles) when man is a link in a control system. This becomes especially important in spaceflight when man must evaluate any eventual situation rapidly and correctly.

These investigations are also of value in designing equipment used to transmit visual signals.

Third, and last, these investigations have become significant in the design of equipment for automatic recognition of images according to the new principles. Investigations of the receptor fields of the retina are important for the design of a system permitting parallel processing of visual information (in contrast with series processing usually used in TV systems). The study of elementary features indicates that it is better to supply a recognition-teaching system not with signals from the receptors, as is done in the perceptron, but with signals that have been made up by standard sub-programs set up on the basis of cutaneous-type receptor fields. Finally, the principle of sequential recognition, /22

as we found it, may have the following significance. The present recognition programs and models of recognition devices are designed for the presentation of single images. A combination of several images, each recognized separately, is a new mode, unfamiliar to such devices. The setup of a system which might find the familiar and unfamiliar, ignoring all else to recognize one or the other, is more rational than sequential analysis.

Now let us examine the third and last problem. Following the original scheme, we will consider two aspects in the system "man-machine-man": man as a receiver of and as a source of acoustic information.

In solving the problem of optimal methods of communicating the necessary information to an operator, it is expedient to distinguish between two types of information. One of them can be defined as information on the essential parameters of the existing situation without evaluating it. In this case each parameter can be considered as a continuous variable. The task of the operator is to evaluate the situation from the observed parameter values.

The other type of information communicated to an operator is information on decisions. The simplest example of a decision is the insertion of an attention or alarm signal in a circuit for the case when the values of an essential parameter have exceeded the permissible limits. It is obvious that in this case it is advantageous to use acoustic signals, since they can be perceived by an operator regardless of his position in the cabin. Considerable difficulties arrive as soon as it becomes necessary to transmit a large amount of information by acoustic signals. It is a well-known fact that the accuracy of absolute recognition of artificial acoustic signals is extremely small. Work carried out at the Institute of Physiology has shown that, in addition, the reaction time to sound when there is a multiple choice increases to a very high degree.

A possible way out of this situation is to use either vocal communication (optimal case) or quasi-vocal artificial symbols.

Shown in Fig. 6 is the capability of recognizing three-element acoustic sequences made up of vowel sounds (Curve 1) or of pure tones (Curve 2). Plotted on the axis of abscissas is the length of each element in the sequence; on the ordinate axis is the percentage of information received. It can be seen that vowel sequences are identified rather well by a human when the length of each vowel is 100 to 200 msec. At such acoustic lengths tonal sequences are not recognized at all. Satisfactory recognition is achieved only when the tone length is increased to 400-500 msec.

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An analysis of this phenomenon was made during a series of investigations, permitting us to come up with some general ideas concerning the mechanisms by which a sequence of acoustic signals is perceived.

A number of experiments led to the conclusion that the volume of the human acoustic memory is highly limited, being approximately equal to 100-200 msec of the acoustic flux. In this connection, man cannot memorize the acoustic image of the entire sequence as a whole; he is forced to make a decision regarding each element of the sequence as it occurs and to memorize the sequence only as a sequence of decisions.

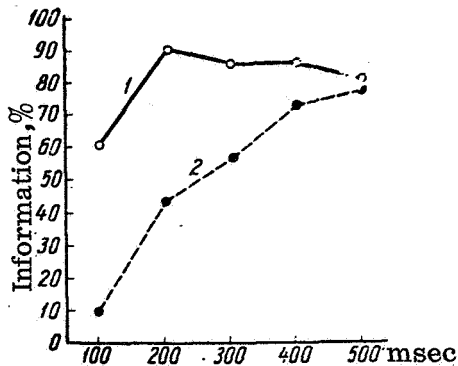


Figure 6. Possibility of Recognizing Three-Element Sequences as a Function of the Length of the Sounds Making Up the Sequences.

1—Sequences Made Up of Vowels (u, a, o); 2—Sequences Made Up of Tone Signals (150, 500, 1600 Hz). The Amount of Transmitted Information is 2.6 Bits Per Sequence (choice of six equally probable sequences).

mately seven syllables. This means that man cannot memorize a long sentence simply as a sequence of meaningless syllables. He must somehow change over to new descriptive elements which will ensure an even more economical representation of data.

The experimental data lead us to believe that the next stage in information processing consists in instant-by-instant selection and analysis of word-forms. A word-form is no longer memorized as a sequence of its syllable or phenome components, but as a set of symbols (grammatical and lexical) characterizing the position of the word-form in a set of possible word-forms of the given language.

In other words, in this space there occurs a transition from description of a message in the space of motor speech symbols to description of the message in the space of linguistic symbols which no longer characterize speech, but language.

It is appropriate to emphasize that all this complexity in organizing speech perception is not at all unnecessary. It is precisely because of this complexity that it is possible to overcome difficulties in processing acoustic information connected with the limited volume of the operative memory. This must be kept in mind when attempting to set up any artificial "language" for acoustic signaling.

A method has been developed for complex recording and measuring articulatory parameters in the dynamics of the speech flow (Kozhevnikov, Chistovich et al.). A number of gauges permits simultaneous and continuous recording of the following indicators in the form of electric signals.

A remarkable peculiarity of speech perception is the very rapid, running re-coding of acoustic patterns into articulatory motor images of the sounds being heard. This is attested to, in particular, by the fact that man can repeat speech that he has heard with very small time delays (120–150 msec).

The large amount of data forces us to assume that the space of motor symbols characterizing articulatory images is considerably smaller than the space of acoustic symbols. Consequently, the transition from continuous acoustic action at the input of the auditory system to its description by a sequence of discrete motor images means that the information has undergone considerable abbreviation, that is, that the data have been represented in a new, highly economic form.

Special experiments have demonstrated, however, that the volume of the operative memory for a sequence of motor images is also not very large, equaling approxi-

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1. Respiratory motion at various levels of the chest and abdomen
2. Pressure inside the mouth
3. The rate at which air is expelled from the mouth cavity
4. The rate at which air is expelled from the nostrils
5. Lip motion
6. Motion of the lower jaw
7. Dynamic palatogram (dynamics of contact of the tongue with various zones of the hard palate)
8. Oscillations of the vocal chords
9. Acoustic pattern in the nasal cavity
10. Normal acoustic speech pattern, recorded by a microphone.
11. Electromyograms of a number of muscles participating in articulation

Figure 7 shows the test subject with the main gauges of the articulatory parameters.

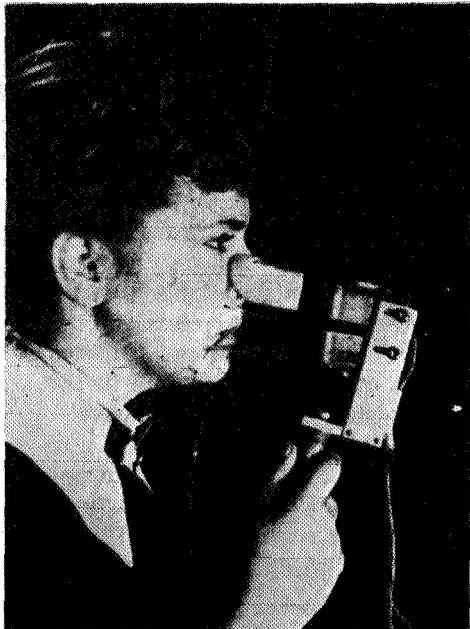


Figure 7. Test Subject With the Basic Gauges of the Articulatory Parameters.

Since it is possible to make an accurate comparison of the time relation between various articulatory phenomena in the dynamics of the normal speech flux and since it is possible to obtain experimental data in a volume completely sufficient for statistics, it is possible to carry out investigations for the purpose of clarifying the following factors: a) the elements making up the speech flux; and b) the general principles underlying the construction of a coherent speech flux from these elements.

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The basic experimental material was compiled from a statistical investigation of the time pattern of articulation during variations in speech tempo, a quantitative study of the phenomenon of artificially stimulated stutter during delayed acoustic feedback, observation of the effects of reduction and overlapping of individual articulatory phenomena, investigation of the peculiarities of speech respiration, and from various other experiments.

This material cannot be presented completely in the present report, but it allows us to state the following concepts regarding the elements and principles of organizing the speaking process.

The fundamental elements which are realized successively in the vocal system to produce coherent speech are complexes of syllable-forming motions. The characteristic feature of syllables in the Russian language (despite linguistic notions) is their open nature; they always end in vowels. Coordination of motion within each syllable is complicated; the effector commands for articulation of the program of a syllable are given with a considerable overlap in time; only motions which are antagonistic per se are carried out in rigorous sequence. As can be imagined, the syllable-forming motions are coordinated primarily on the lowest levels of the nervous system. Thus, a syllable can be considered as a sort of a "block" in which a definite part of the program of speech synthesis takes place. /26

In coherent speech, syllables are combined to form larger units in the "physiological organization" of the speech flux-syntagmas. A syntagma can be defined on the basis of certain features-speech respiration: the intrapulmonic pressure is observed to be maintained continuously over the entire extent of each individual syntagma, and intake is possible only between syntagmas. Thus, the syntagma is a longer section of the program that controls speech synthesis. It contains a definite sequence of syllables that is realized in a certain complex rhythm.

A diagram of the basic operations that are carried out in the synthesis of syntagmas and syllables in the spoken language is shown in Fig. 8.

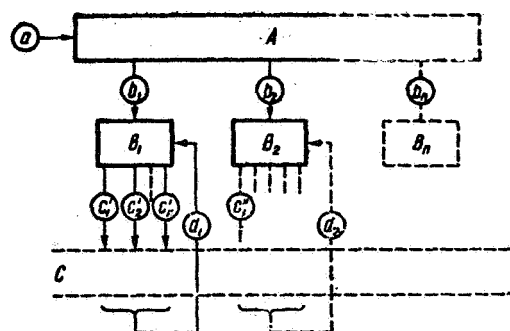


Figure 8. Diagram of the Operations Performed in the Synthesis of Syllables and Syntagmas.

A—Block of the Syntagma Program; $B_1, B_2, \dots, B_n$ —Blocks of the Syllable-Forming Program; C—Articulatory Motions ("effector organs"); a—"Triggering Signal" for the Syntagma; $b_1, b_2, \dots, b_n$ —"Triggering Signals for the Syllables; $c_1', c_2', \dots, c_n'$; $c_1'', \dots, c_n''$ —"Triggering Signals" of the Articulator Motions; d_1, d_2 —Signals for Correcting the Syllable Program.

The sum total of the data obtained in the study of the dynamics of the articulatory motions of the spoken language permit us to make the following statement. Obviously, the transition from a sequence of phoneme symbols describing the sentence program at higher levels of speech control to a sequence of articulatory motions is accomplished in part by arranging the sequence in groups, each group being terminated by a vowel. Groups of symbols are fed one by one to the input of the motor system and are used to synthesize or select the corresponding articulatory complex made up of syllables. This makes it possible to ensure an extraordinarily high rate of generating information by speech.

Of course, such a method of solving the problem of increasing the information transmission rate is possible only when the number of muscle groups involved in producing the complex, i. e., the number of /27

different articulatory complexes, is very high. For instance, the number of different simple syllables in speech amounts to several thousand. Moreover, coordination of motions within each complex must be very precise, as is the case in speaking.

These facts induce us to assume that it is unrealistic to propose the possibility of developing a new, artificial system of motions that could be used to provide the same rate of information transmission as in the case of speech motions. Attention should also be called to the rather remarkable fact that the transmission power of the visual system and the speaking organs coincides (50 bits/sec), a fact which indicates that there is good agreement between the amount of information processed at the "input" and "output" of the nervous system. Obviously, voice communication is the most promising way of transmitting information from an astronaut to the equipment. This means that researchers must devote serious attention to the development of equipment for the automatic identification of speech.

PSYCHOPHYSIOLOGICAL CHARACTERISTICS OF THE
SOLUTION OF MOTOR PROBLEMS
BY MAN

N. A. Rokotova

The further development of space flight is dependent on the reliability of the human being as a biological system, that is, on the degree of his resistance to unfavorable flight factors as well as on the limits within which he can be trained to be stable to such factors. However, even successful solution of the problem of the reliability of the human being as a biological system does not furnish a complete answer to the problem.

The second aspect of this problem is intimately connected with determining the control and communication functions that can be entrusted to an astronaut. Obviously, it is expedient to have a man aboard a spacecraft when we think that he will be able to carry out those functions of controlling a spacecraft, the communication system and the flight situation as a whole that even the most highly perfected machine cannot do.

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At the present time, psychology and physiology are hardly in a position to provide a clear answer to this question, since it has never risen before in this formulation and since it still requires much and varied research. Obviously, this research work will have to develop along two principal equal lines: 1) a theoretical study of the higher nervous activity of man within the scope of the problem "man as a link in a control system"; and 2) a study of the specific control functions, under optimally real conditions, using trainers, simulating some of the actual equipment of spacecraft control systems.

At first glance it may seem that the second line of research will yield a clean answer to the question as to whether and how man can handle the control systems simulated in the trainer. However, a closer examination reveals that such a method can never yield a fundamental solution to this problem or a prediction of human behavioral patterns under work conditions with certain new, untested control-panel designs or under conditions in which new problems arise.

At the present time, study of the higher nervous activity of man urgently requires analysis of his effector activity. As technology develops, the effector activity of man, being most completely representative of his professional acumen, is changing more and more distinctly from the category of motor skills to what may be called the solution of problems.

In this connection, the most important of the requirements imposed by such type of activity are those on the higher organs of control of activity itself, on the higher nervous activity of man. At the same time, the classical ideas of the higher nervous activity of man do not include an analysis of his effector activity; in essence, they reduce this activity to a sum of simple single actions (answers) to signals from without. Such ideas are insufficient, because in our opinion they

do not contain the principal characteristic of higher nervous activity, which involves organizing the process of doing something and which determines every kind of human activity, especially professional activity.

The aim of the present paper is to summarize the experimental work and the resultant hypotheses on the methods of organizing the effector activity of man. The experiments were carried out by a team from the I. P. Pavlov Institute of Physiology (N. A. Rokotova, I. D. Bogina, I. M. Gorbunova and Ye. S. Rogovenko) from 1962 to 1965.

Dynamic Human Stereotypes as Programs

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Precision of action is ensured when the motor act is organized in such a way that the process is completed by the minimum groups of muscles necessary for the given problem and that the muscle contractions of these groups are time-correlated. Economy of motion is further narrowed down by saying that the effort exerted by each muscle and group of muscles can also be said to be the minimum necessary to solve the given problem [28]. However, organization of the motor act does not exhaust the problem of organizing action, since we are still left with the problem of correlating individual motor acts. In its most obvious form, this question arises when the complex of motor acts consists of several motions, each of which is familiar to the human being (i. e., the motor act itself is organized with respect to coordination).

This is true of motor acts in which machinists or pianists depress keys or an operator standing at a console presses buttons or turns handles. How does a man who skillfully performs a sequence of actions differ from an untrained man? One of the possible answers is that skillful performance is distinguished by the highest precision and by the rate at which individual motor acts are carried out in succession. In the opinion of various authors the reasons why motor sequences are carried out effectively can be found: a) in the motor system itself; b) outside the motor system; and c) within the framework of control of motor acts.

The first viewpoint, which was formulated by Campbell [7] as early as 1936, reduces to the existence, so to speak, of general motor or technical capabilities. A corollary of this viewpoint is that there should be some correlation between the level with which one motor skill is performed and another. However, the numerous studies made by Seashore [15] on the basis of a large amount of material have proved convincingly that this viewpoint is without foundation and that there is no correlation between different forms of motor skills. Seashore's results indicate that the performance of individual types of sequences of actions is of a very specific nature and lead us to believe that actions are organized at the level of some definite sequence or motor problem, governing the specific nature of the given motor skill.

The basic concept underlying the second viewpoint is that the level of the motor skill (performance) is determined by the logical side of the problem, i. e., by the flow of information received from without. This is the reason for the many investigations of the motor response time as a function of the physical and informational characteristics of a signal. A number of studies [5, 25, 26]

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demonstrated that a response time of 100-150 msec to a single signal increases, e.g., to 800 msec when the signal carries eight alternatives (possible decisions), that is, three bits of information. On the basis of this viewpoint, let us consider the work of a trained typist typing some text from a sheet of paper. We know that a letter of the Russian alphabet carries 5 bits of information (there are 32 letters, i.e., it is possible to make one of 32 decisions in recognizing the letter on the keyboard before pressing the key). This quantity is distinctly greater than the one (3 bits) that requires no less than 800 msec from the time the signal is produced to the time the key is pressed. Let us assume that this time does not increase beyond 800 msec. This means that the rate at which the typist should work is somewhat more than one letter per second. This is a rate which corresponds approximately to the concept of "channel capacity" in communication theory; in magnitude this rate is similar to the experimentally determined transmission capacity of a human [30], which amounts to about 6 bits/sec. At the same time, we know that an experienced typist can type 4-6 symbols per second. Special studies of the amount of information at such speeds have shown that the quantity of information in this case would be about 25-30 bits [32, 33].

Such a serious discrepancy between the real performance index of an experienced typist and the theoretical level that might be achieved if the speed and accuracy of the work were governed only by the flow of input information indicates that these concepts are insufficient.

The third viewpoint combines the reasons for the effectiveness of motor skills and control of motor acts and develops ideas as to the hierarchy of programs that can be used to control the different variables that make up an organized sequence of motor acts. The program is a certain description of the performance process. It may resemble a sheet of paper with written instructions concerning the enumeration, order and method of performing individual operations making up the given motor problem. In other words, the program is a sum of the instructions as to how a problem is to be carried out (such instructions for the typing operation might be: find the necessary letter, identify, move the hand, put the finger in contact with the keyboard, lift the finger, check the result, etc.).

A hierarchy of programs is a concept relating to a stratified programming structure, which is reminiscent, e.g., of the structure of administrative control. The top command level gives only the most general instructions which, as they descend the hierarchical ladder, become progressively more fragmental and specific. It can be imagined that the lowest rung of the ladder of motor programs is a set of instructions to definite groups of muscles ordering them to contract, so as to give finality to the required work posture, whereas one of the highest rungs is associated with instructions for prescribing the order of the actions involved in the task (using the typist as an example, take a piece of paper, insert it, transport the lines, type, etc.) and for prescribing the working mode (the speed which governs the length of the intervals between individual actions). /31

Ideas on behavior as a sort of program are not new in physiology, even though they have only recently been given the impetus for rapid development as a result of the success achieved in other branches of science. In his investigations I. P. Pavlov came quite close to a similar idea, as is indicated by such approaches in his work as the consideration of a dynamic stereotype, time reflex and reflex when a reference is made to a point of reinforcement in a series [9]. In 1963

Asratyan [2] pointed out the program nature of a stereotype. Furthermore, we should mention the ideas proposed in 1947 by N. A. Bernshteyn relating to the steps involved in motion [3]. The voluminous evidence cited by the author concerning the description of certain motor tasks is a convincing argument that actions are carried out according to a program.

In 1951 Lachley [27] formulated the idea that the principles of various forms of behavior (verbal, motor, professional) are general. He examined the order of actions in a sequence and stated that not only speaking, but also motor acts present us with the problem of time integration of the sequence, the problem of ordering individual activities in a certain time interval.

In the last four years the development of programming concepts as the basic principles for understanding behavioral mechanisms (especially motor problems) is characterized by the appearance of a number of works of theoretical nature in which various schemes for program control of behavior are suggested [4, 19, 24, 31]. The authors of these articles have brought forth many useful arguments, but the physiological value of the schemes they proposed is as yet unclear.

The development of programming concepts in describing the behavior of man has a number of advantages over other representations of human behavioral mechanisms. It has simplified, e.g., understanding of certain pathological forms of behavior such as apraxia, because they can be examined as a disease of the programming mechanisms. Simplified in the same way is the description of certain conditioned-reflex forms of behavior such as the time reflex or reflex to alternating reinforcement. In order to describe conditioned time reflex in the language of conditioned reflexes, it is necessary to draw on a number of additional explanations, since the conditioned time reflex does not contain a conditioned signal in the usual sense, and it cannot be realized only once. However, the features characterize the usual conditional reflexes. The idea of a program that can be used to deliver individual responses over equal time intervals simplifies the understanding and description of conditioned time reflex. /32

Thus, the problem of programmed behavior mechanisms is very important to the science of higher human nervous activity, and in this connection it must be noted that the amount of experimental investigations in this domain is unaccountably small.

In 1932 Lamley [8] demonstrated that man can be taught a series of actions formed only on the search principle. A man stood before a typewriter and was presented the problem of selecting a letter in the mind of the experimenter. Since the experimenter had a program with a fixed order of letter choice, the test subject could discover the experimenter's system of actions and could reduce the number of searches by formulating a system (stereotype) of responses. Subsequently many authors carried on their work using the search approach to study systematic behavior. This type of problem is an example of a certain stereotype developed without the aid of external signals.

I. P. Pavlov showed that the idea of a stereotype consists in the formation of a connection between individual conditioned reflexes by repeating their order of sequence. The classical proof of this fact is the experiment in which the external conditioning signals were discarded, leaving the order of succession of the responses unchanged.

In our experiments it was shown that the property of a stereotype to control the order in which responses are made is stable, making it possible not only to eliminate signals after the stereotype has been taught, but also to organize the process of teaching a stereotype independently of external signals. This property was studied by us both in higher animals and in man [11, 12, 13].

The existence of forms of behavior in which knowledge of the response to be made is based on interrelationships between responses distributed in a certain order raises the problem of control programs in which the position of each response in the sequence is fixed.

The fact is, as our experiments have shown, that man is capable of developing stereotypes of up to 48 components in length without external signals [14]. Since such stereotypes do not contain signals indicating which response can be found, say, in the 36th position of the stereotype, such indications must be provided by some sort of control mechanism. In order for such a mechanism to issue responses, while preserving a strict order, it must be either of the computer type or must be based on relations between individual responses. A mechanism which counts the number of components in a stereotype when the stereotype is of considerable length is uneconomical and cumbersome. A mechanism based on relations between responses is more favorable, because not all the responses in the stereotype need be enumerated, a relationship need only be established between several responses. Let us illustrate this with an example.

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Let us imagine that we have presented a man with the task of developing a stereotype under the condition that there are two signals (denoted below as "red" and "green") which are to be used in making one of two responses, say, depress one of two buttons. The stereotype consists of 9 units; the order of sequence of the signals and responses is presented in Columns 2 and 3 of Table 1. The problem is: how will the man behave after developing the stereotype if we get rid of the signals and change them by repeating one signal, e.g., the red one? From the classical experiments we know that in the same situation animals repeat the number and order of the responses developed in the stereotype. But in this case man, more often than not, will begin to repeat response 1, which is related to actuation of the red signal. At the same time, if he is asked to repeat the learned order of response to the action of only the green signal, he will be able to reproduce this order. This means that the mechanisms governing the response activity of man under such conditions involves, in addition to fixation of the order of responses, the formulation of a rule of the type "the red signal requires the first response." In connection with this rule it has proved to be possible, e.g., to make any arbitrary increase in the number of signals and to make any combination of them. Thus, the sequence of response actions ceases to be dependent on the number of signals used, but is based on a rule connecting a specific signal with a special response.

This is one aspect of the response activity. Another aspect is connected with the fact that a human being repeats the order of events, when the order of the signals is changed, by repeating one signal. In the case of the stereotype described in the left half of Table 1, in order to reproduce the order of events it is necessary either to memorize the entire list and order of the signals and use the rule whereby the signal is related to the response or to memorize the entire

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TABLE 1. Problem of Developing a Stereotype With Two Signals

Successive numbers of the stereotype units	Original order of the signals	Order of the responses	Change of the original combination	Order of the responses
1	2	3	4	5
1	Red	1	Red	1
2	»	1	»	1
3	Green	2	Green	2
4	Red	1	»	1
5	Green	2	»	2
6	»	2	Red	2
7	»	2	»	2
8	Red	1	Green	1
9	»	1	Red	1

list and order of the responses. In either case, the delivery of a response in the stereotype order evidently requires enumeration of all the components of the stereotype.

Hence, analysis of such stereotype still does not yield an answer to questions concerning the mechanisms which indicate position in a stereotype on the basis of knowledge of the relationships between neighboring acts. Now let us turn to the right half of Table 1. Here we are also dealing with a stereotype as well as with a definite order of the responses. Here, however, the relations between the individual responses are governed by other characteristics.

The fact is that this characteristic is based on rules governing the relations between three events: two neighboring actions—the past and present—and the present signal. Man can formulate these rules for himself approximately as: "on the red signal stay where you were the last time; on the green signal, change position." In this kind of stereotype the order of signal succession can be completely random, whereas the response behavior is completely systematic. The system of responses in this case is connected with the acting signal as a condition defining which signal is to be used in giving the next response. Such relations between external signals and responses are similar to the input and system relations in technology, and therefore we have denoted Column 4 of Table 1 as a "replacement of the input signal combination." This kind of stereotype was developed in more than 30 men [14].

It is clear that the possibility of experimental development of such behavioral systems in man leads us necessarily to ideas of control programs and to clarification of the problem of the component parts of control programs.

The Teaching Process as Synthesis of the Order-of-Action Program

In 1948 Woodworth formulated the motions of two-phase and polyphase motor units [34].

Expanding his notions, Fitts discovered the nature of the polyphase unit and stated that it may be precisely this unit which is a component part of the performance program [24].

The concept of a two-phase motor unit is a concept relating to a single motor act such as grasping, pressing, throwing, jumping, and consists of a preparatory phase (to squeeze it is first necessary to open one's fingers) and an effector phase (the grasping act proper). In its simplest form a polyphase unit is a sequence of several two-phase units, that is, a larger or longer piece of motor activity which, obviously, is somehow connected (e.g., connected with the fact that individual acts are successive in time and are done repeatedly in the same sequence).

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In our experiments we found that individual acts are grouped together in a motor sequence. Subsequently we made a special study of this fact, so that now we possess data which enable us to single out the individual forms which the phenomenon of action-clustering takes on [12, 13]. Let us consider some examples.

Magnitude of the Gain in Number of Actions During the Learning Process. Imagine that it is necessary to memorize a certain sequence of motor acts, and that this sequence is so long that it cannot be memorized at one time. Let us say that the sequence consists of 36 individual actions. Let us consider a teaching method in which the entire chain of events that must be learned is somehow presented, and each time it is presented we will ask that what was memorized be repeated.

The general course pursued in solving such problems reduces obviously to the fact that the number of the repeated actions increases from presentation to presentation until all 36 actions are reproduced. The question arises as to how many actions are added to the part already learned in one showing or for each repetition. In our laboratory we carried out experiments aimed at solving this problem. In brief, the essence of the experiment reduces to the following. We made up two problems of learning and repeating a sequence of actions. Each action consisted of pressing one of eight keys of a special panel. The keys were arranged in two rows of four each and occupied an area of 8 x 20 cm.

Both problems contained 36 actions to be accomplished in different order. In setting up the sequential list of actions we took into account the location of the keys over the surface of the panel. From our previous experience we knew that people lump together individual key-pressing actions on the panel when these actions are carried out on keys in a row or when the transfer of the hand from one key to the next described some geometrical figure. This fact served as a basis for putting together the problem in this series of experiments. The 36 actions of which problem 1 was composed were arranged in such an order that every four actions (first to the fourth, fifth to eighth, etc.) could be lumped together. In problem 2 the 36 actions were arranged in such an order that every 3 or 6 actions could be grouped together.

The learning procedure consisted of instructions in which the problem was to learn and repeat the order of the 36 pressing actions, of the learning process itself and of the subsequent multiple repetition of the stereotype by heart. The procedure was carried out by repeatedly demonstrating to the test subjects the

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entire sequence of actions, followed by a repetition of what had been acquired (immediately after terminating the demonstration). A set of eight light signals arranged in the same way as on the panel served for the demonstration. The test subjects were acquainted with the unique relationship between the signal and the key and were then shown the order of the actions by consecutively flashing the respective signals.

A twelve-man group of test subjects was selected to learn both stereotypes. One half of the group was taught problem 1, and three days later problem 2; the second half fulfilled this task in reverse order.

In order to solve the problem of the magnitude of the gain we counted all differences in the number of repeated elements between successive repetitions in the learning process. For example, if the test subject repeated 6 actions after the first presentation of signals, 10 after the second and 13 after the third, the respective differences making up the magnitude of the gain was 6, 4, and 3 actions.

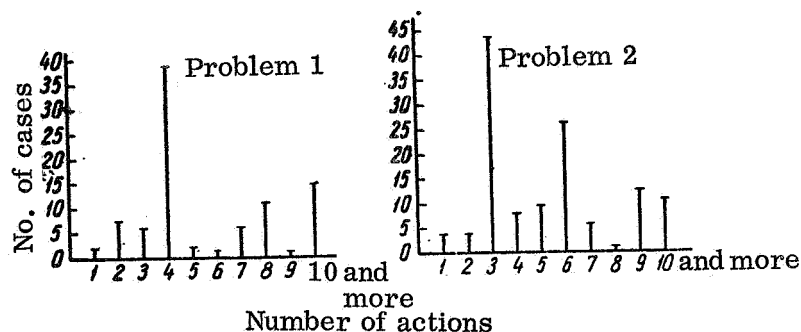


Figure 1. Distribution of the Number of Actions Gained in Each "Step" of the Learning Process as a Function of the Structure of the Problem.

Shown in Fig. 1 are summary data covering the entire group of test subjects, characterizing the size of the gain from repetition to repetition. From the figure it is evident that cases of only a single-action gain are the rarest. Most frequent are the magnitudes of those gains which correspond to the structural features of the problem (4 actions for problem 1 and 3 and 6 actions for problem 2). Consequently, the learning process is of a nonuniform, discontinuous nature, the nonuniformity evidently being connected with the formulation of a control program consisting of certain blocks containing several clustered motor acts.

A more detailed description of this series of experiments is given in an article written in conjunction with I. M. Gorbunova: "On certain features of programming a sequence of human actions," which can be found in this collection. /37

Transposing Blocks of Actions in Learning a Stereotype. The discontinuous nature of the process of learning a stereotype is associated with the blocking process, that is, coupling individual responses into certain blocks. There is

reason to believe that these blocks have the character of a new, closed behavioral unit (not unlike the polyphase motor unit of Woodworth and Fitts). In experiments on a 30-man group of test subjects who learned a sequence of 36 actions (problem 1 given above) we analyzed the responses of the test subjects from the viewpoint of coincidence between a sequence of responses and consecutive positions in the stereotype. The results of this analysis are given in Table 2 in the form of a distribution of errors committed by the group of test subjects during the same learning periods. Selection of the errors committed by the test subjects was based on the fact that a correct response was considered to be only a response made at the point that corresponded to its correct position in the stereotype. Hence, the responses which reproduced individual elements of the stereotype, but were not made at the correct points, were considered as errors. In such a context it was found that the bulk of the errors stemmed from clustered actions arranged in an order that differed from that in the given stereotype. As is evident from Table 2, after 20 learning repetitions, 55% of all errors were due to the fact that clusters of responses corresponding entirely to specific parts of the problem were not reproduced at the correct points; the remaining errors were also connected with the effect of grouping actions. Only 20% of the errors were not connected with coupling of actions into blocks.

TABLE 2. Error Distribution in Repeating a Sequence of 36 Actions

Learning level	Overall number of errors	Error distribution (%)					
		Total errors	Trans-position of correct blocks	Transposition of distorted blocks	Total no. of group trans-position-errors	Simple grouped errors	Random errors
After 10 repetitions	510	100	38	23	61	37	2
After 20 repetitions	385	100	55	21	76	22	2

Remark: 30 test subjects participated in the experiments.

Thus, the integrity of a block of actions is supported by the fact that the block was freely transposed, while preserving the order in which the coupled motor acts were arranged.

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Selection of Coupled Blocks of Actions. The nonuniform, or discontinuous nature of the learning process is connected with the process of clustering actions and comes to light in another way. If the stereotype is learned from the very start without any relationship with specific signals, but by searching for or guessing each individual consecutive action, it turns out that the order in which individual actions are acquired does not correspond to their consecutive positions in the stereotype.

Twenty test subjects worked through a stereotype consisting of 20 actions, each of which had to be found from among 8 possible motor acts (in somewhat the same way as with Lamley's printer). During this test not once did we observe the process of accumulation of a sequence of correct responses, which would

have meant a gradual increase in the number of terms as well as maintaining them in order (first the 1st term of the stereotype, then the 2nd, 3rd ... 20th). A typical case of learning such a stereotype is shown in Fig. 2, which presents the experimental record of test subject V-ts. The black squares, which show the positions of the correct responses, clearly demonstrate the presence of the process of coupling individual correct actions and of singling out a coupled group of responses to which more and more new responses are added to each side.

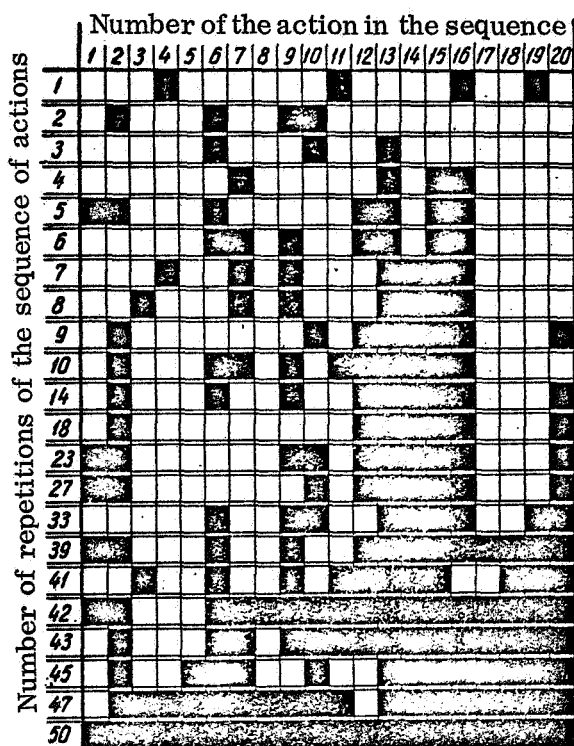


Figure 2. Experimental Record in Learning a Stereotype by the Search Method. (Test subject V-ts.) The Open Squares are Errors, the Solid Ones Correct Responses.

Thus, there exists a number of proofs of the fact that learning of a stereotype is connected with the process of forming, singling out and combining groups of motor acts.

Coupled blocks of response actions are built up in such a way that it is possible to give a general description of a block. This indicates that the human control nervous system has a program-type of control mechanism in which concrete programs are set up (synthesized) in learning a new motor problem. Evidently, under the conditions of the problems described above, the programs are composite, consisting of several elements or subprograms, such as the structures that ensure the execution of a coupled group of actions.

CENTRAL MECHANISMS GOVERNING THE TIME DISTRIBUTION OF MOTOR ACTS

Rhythmic Pattern of the Time Distribution of the Process of Executing a Stereotype of Actions

In order to formulate a hypothesis on the location of the grouping process in mechanisms of the control program, it is necessary to draw on ideas relating to the hierarchical structure of programs, which was discussed at the beginning of the article. In connection with the above-described results of analysis of the stereotype learning process, it might be assumed that the process of forming a block is independent of the process of joining blocks. Then, based on published viewpoints on the hierarchy of programming mechanisms, it is permissible to assume that block-forming processes reflect two levels of mechanisms in the control program.

The upper level issues instructions on the order in which blocks of responses are made, whereas the lower level controls the order in which the individual responses making up the blocks are delivered. If this hypothesis is correct, it can be expected that the total time for performing a stereotype will not be uniformly distributed. In particular, it can be expected that the interval separating adjacent actions of different blocks will be different from the interval that separates adjacent actions of one block.

In connection with these ideas we made repeated measurements of the time for performance of a stereotype after learning the above-described problems of a sequence of 36 key-pressing operations. Measurements were made of all the time intervals for performing the sequence of actions.

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A tenfold record of the performance of the stereotype was made on a multi-channel loop oscillograph and measurements were made by examining the tapes on a photoamplifier provided with a measurement grid. We measured the time spent by man in executing the individual actions of the stereotype and the length of the pauses between adjacent actions. For each test subject we computed the average values of ten measurements and then computed the arithmetic means of the group of test subjects and the rms deviations.

Presented in Fig. 3 are data on the length of the pauses between individual motor acts as a function of the location of the pause in the stereotype. Given in the upper half of the figure are the values which characterize the execution of problem 1 and in the lower half, of problem 2. Verticals were drawn from the peaks of each curve. From the figure it is evident that the distribution of time intervals is specific for the execution of each problem. Thus, the peaks of the curve characterizing the execution of problem 1 refer to the 8th, 12th, 16th and 20th positions, while those of the curve describing problem 2 relate to the 6th, 9th, 12th, 15th and 18th positions of the stereotype. The values of the rms deviations, which characterize the degree of individual scatter, do not overlap the characteristic rhythmic pattern of each stereotype.

Thus, the rhythm of the time pattern of a stereotype is described by the greater magnitude of some pauses as compared with adjacent pauses. The longer pauses are found at the points where the individual blocks making up the stereotype join. The fact that the problem is specific shows up in the number and size of the groups and is detected in the distribution of the completion-time intervals. Consequently, clustering is that sign of an ordered sequence of actions that characterizes not only the learning process but also the execution process.

It must be noted that a number of authors have drawn attention to clustering phenomena in other forms of motor problems, such as alternating motion of the right and left arms [10], load-lifting motion [16], walking in a maze [23], as well as in other forms of response activity (repetition of a sequence of letters by naming them [20]).

Stability of the Rhythmic Pattern of a Stereotype. The idea that the distribution of the time intervals in a stereotype creates the specific rhythmic pattern of the problem can be strengthened and verified by investigations devoted to the stability of the rhythm to a change in the overall working speed as well as to the degree of training of the test subject for the given task.

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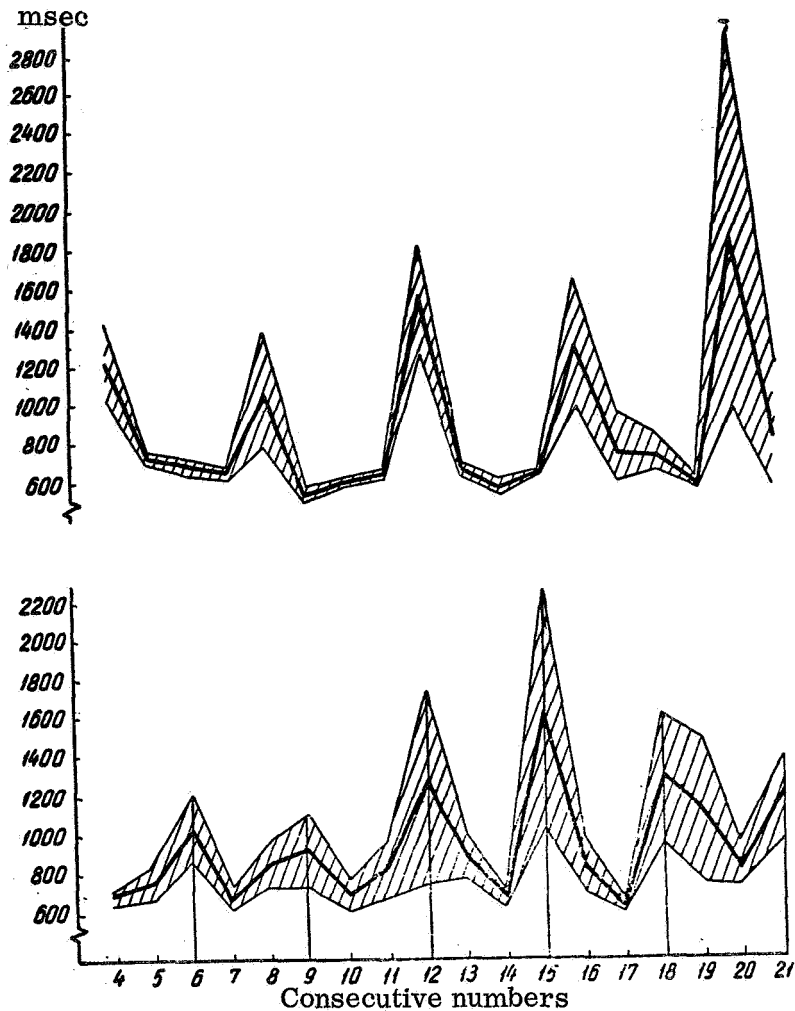


Figure 3. Time Distribution (pauses between adjacent actions) in Carrying Out a Stereotype as a Function of the Structure of the Problem.

Formulation of the problem of the effect of speed on the rhythmic structure of a sequence is due to L. A. Chistovich [18], who demonstrated that the rhythmic structure of the spoken language does not change with the speed. In our research we found similar facts applying to the execution of motor tasks. The experiments were conducted in the following fashion: After learning a sequence of 24 actions, 15 test subjects were required to carry out the sequence several times at their best speed. At the same time the experimenter noted the time it took to perform the task. Then he asked the test subject to work at precisely that tempo as smoothly as possible and to keep within a time interval limited by start and finish signals. The aim was to make the last action of the test subject coincide with the finish signal. Ten executions of the stereotype were recorded on the oscillograph at this original tempo. In addition, the test person was asked to reduce the tempo by one and a half. Now the finish signal was given after a

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start-finish time interval greater by a factor of one and a half than the original one. Ten executions of the stereotype were recorded at this tempo. Finally, the test subject was asked to return to the original tempo and again ten executions of the stereotype were recorded. Each time the tempo was changed the experimenter changed the time interval limited by the two signals so as to correspond. The results of measuring the individual time intervals for executing the stereotype revealed that the rhythmic pattern of the problem was preserved when the work tempo was changed. These data are shown in Fig. 4. Each point represents the arithmetic mean of ten measurements of the period required to perform an individual act (the time it took to move the hand plus the pressing time) expressed in fractions of the total period during which the task was fulfilled. It is clearly evident that the rhythmic pattern of the stereotype is invariant, indicating that the temporal distribution of actions in a stereotype is stable with respect to the overall performance speed (tempo).

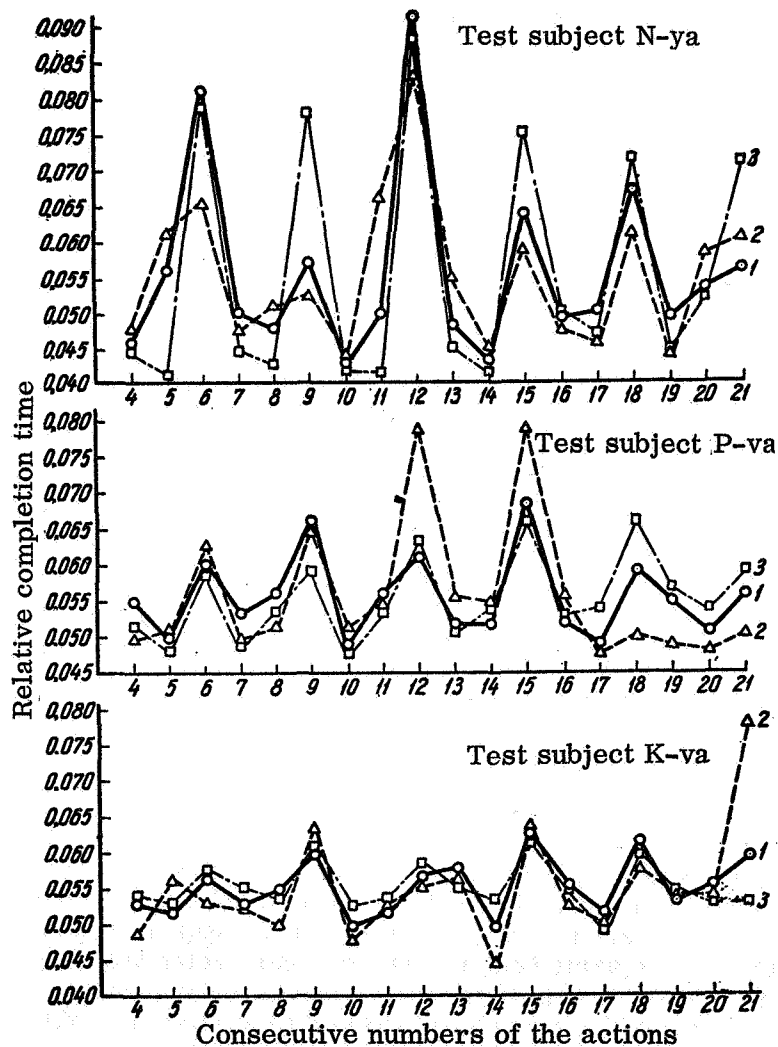


Figure 4. Distribution of Time During the Execution of a Stereotype at the Optimum Tempo (1), at a Tempo Slower by a Factor of 1.5 (2) and at a Tempo Accelerated by a Factor of 2 (3).

In others of our experiments it was found that the rhythm is stable to repeated execution of the task. Six test subjects were trained in a hundred repetitions to execute the same sequence of actions. The "automatic" nature of the performance was tested by asking the test subject to count the light flashes aloud while executing the task. It was found that the rhythmic pattern of a stereotype remains invariable.

Thus, the specificity of the control program consists in the existence of such characteristics in the learning and performance process as the association of motor acts in groups as well as in the stability of these characteristics to certain perturbing effects.

The Process Underlying the Uniformity with which a Stereotype of Actions is Performed

In studying the process of performance of a sequence of actions by a human being we directed our attention to the uniformity of the work of the test subjects. Repeating the same series of experiments over and over again with an unspecified time schedule, man sets his own schedule, so to speak. This is evident from the fact that the total time it took to carry out the series of motions became stabilized. In experiments carried /44 out by Miss Savilova, a student, the test subjects repeated a learned sequence of key-pressing actions on the experimental panel tens of times. The sequence consisted of 36 motor acts executed always in the same order. Each pressing act was recorded on a multichannel recorder with a moving-picture film. Counts of the time it took to execute the sequence revealed that each test subject repeats it within a certain fixed time interval. Thus, test subject K-va performed the series of motions in 18.910 ± 0.130 sec (76 measurements), while test subject T-va executed the same series of motions in 26.150 ± 0.310 sec (45 measurements). The mean error in the first case was 0.6% of the arithmetic mean, and in the second case 1.2%. Such high accuracy in repeating one and the same time interval cannot be accidental. At the same time, the work tempo was not prescribed in any way; the test subjects freely repeated the series of learned motions from memory at an arbitrary tempo. Hence it was postulated that the human nervous system contains a mechanism which controls time intervals.

There can be no doubt but that the central nervous system of man possesses the property of measuring time intervals. The widely known work of Pavlov's school on conditioned reflexes to time clearly illustrates this property [9]. In recent years, the investigations of M.A. Alekseyev et al. [1] have shown that man estimates time intervals with a high degree of accuracy. In all these cases we have been speaking about the measurement of time intervals limited by signals external to the human being, that is, of imposed rhythms, not of natural ones. But whenever man works at a certain tempo fixed by himself and not limited by external signals, it is necessary to be capable not only of measuring time intervals, but also of generating them. It is natural to assume that the nerve system has this property also. Rhythmic contractions of the heart, walking, running, swimming and many other forms of activity are obviously sequences with a specified rhythm or (what is the same) with fixed intervals. The well-studied fact of the diurnal rhythm inherent in living organisms is understood by many researchers as the generation of internal, so-called circadian rhythms [6].

A model of a mechanism generating time intervals of the length in which we are interested was studied by McGill [29]. The basic mechanism generates regular excitations which, however, cannot be observed. Accessible to the observer are the responses, each of which arises as the result of successive excitation, with a certain random delay. Hence, the observed intervals between responses contain a random component (delay) and a regular component (fixed interval). Shown in Fig. 5 (from McGill) is a diagram of such a mechanism, where τ is the time interval (fixed) between two excitations, S is the delay between successive excitations and the instant the response is made (random), r is the time interval between the successive response and the next excitation, and t is the observed interval between responses.

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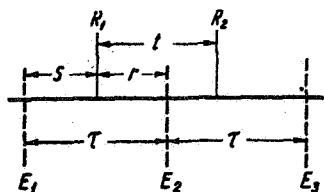


Figure 5. (From McGill).
 E_1, E_2, E_3 are regular
excitations:

τ —is a fixed time interval between excitations; S —is the random delay between excitation and response; r —is the interval between a response and the next excitation; R_1, R_2 — are responses; t — is the observed interval between responses.

McGill shows that the distribution of S is not completely random, but that it is limited by the presence of a fixed interval τ , and therefore the values of S are distributed not in the interval $0 \leq S \leq \infty$, but in the interval $0 \leq S \leq \tau$. Hence, the distribution of the observed interval t differs from the normal distribution of the random function; in simplified form, it can be represented as the distribution of the Laplace function describing the operation of a periodic mechanism under "noise" conditions created by the random delay.

We believe that McGill's model may be a useful working hypothesis in analyzing the time it takes to complete a sequence of actions. An attempt to apply the model to a series of monotonic motor acts (pressing of keys) may help to explain the question of what is a unit (a fixed time interval τ) in a sequence of actions.

Under our experimental conditions, which were described in detail in [13], three levels of fixed intervals may exist: A—an interval during which the whole learned series of motions is carried out; B—an interval during which a group of actions less than the whole series, but containing more than one action, is performed; and C, c—intervals separating one action from the next. Hence, the problem of the present research reduced to measuring the intervals A, B, C, and c while repeatedly executing the learned sequence of actions (pressing keys on a panel) and to analyzing the distribution of these intervals. At the same time we expected to obtain one of two possible results: 1) if the given interval proves to be unspecified, its distribution may be close to normal; and 2) if the interval is fixed, its distribution differs from the normal and, according to McGill's model, approaches the distribution of the Laplace function.

Method

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The experimental setup consisted of two large panels (25 x 30 cm). The test subject's panel contained 8 signal lights arranged in two rows of 4 each,

and 8 keys arranged in the same order. The experimenter's panel had 8 buttons to control the signal lights and 8 monitor lights for observation of the test subject's actions. The test subject was asked to learn and repeat a series of key-pressing actions on the panel several times, the series consisting of 36 or 24 successive pressing actions to be accomplished in a definite order. The pressing order was specified by the experimenter and was set up in such a way that the entire sequence could be divided into blocks of successive actions. In carrying out the actions making up a block the hand traverses a path forming, so to speak, a definite geometrical pattern or figure on the panel (e.g., a square, zig-zag, triangle, etc.).

The test subjects were persons of both sexes, in the 18-45 age range, with high-school or college education, and were volunteers.

The experimental procedure. As a preliminary, the test subjects were trained to execute a series of key-pressing operations on the panel in a certain order. After learning the series, they were instructed to reproduce the learned order of actions from memory. In different experimental versions, the test subjects reproduced a series of pressing actions from 10 to 100 times. The completion time was not specified in the majority of the experiments; in one series the time of completion of the sequence was prescribed, being controlled by the light signals: the experimenter noted the time of completion of the task, established a mean for each test subject, and then informed each test subject that it would be necessary to work each time within the same time interval. To do this, light signals were introduced, one giving the order to start pressing keys, the other (terminal) to coincide with the start of the last operations. The length of each specific interval corresponded with the average time it took the respective test subject to complete the task.

Recordings of the actions of the test subjects were made on the tape of a multichannel loop oscillograph. The tape speed was 4 mm/sec. The key-pressing motion was recorded on the tape in the form of a rectangular pulse. The pulse length corresponded to the key-pressing time. The separations between intervals corresponded to pauses between two pressing actions (the time it took to move the hand from one key to the next).

The parameters were measured on the tape by means of a photoamplifier, with a measuring grid, having an accuracy of up to 50 m sec. Let the time of completion of the entire sequence be denoted by A (Fig. 6). It is the sum of all the intervals ($l_1, l_2, \dots, l_n$) during which the keys were pressed and of the intervals ($c_1, c_2, \dots, c_m$; $C_1, C_2, \dots, C_k$) between pressings. The "c" intervals separate actions within a cluster, the "C" intervals separate clusters of actions. The segments $B_1, B_2, \dots, B_{k+1}$ represent the time expended in executing a block of actions.

Analysis of the Measurements. Over all the above-listed intervals we calculated the average values and the rms deviations, estimated the distribution, and computed the relative errors (σ/x) and relative errors of the mean (m/M).

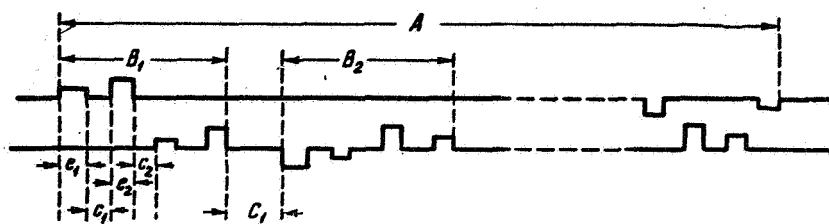


Figure 6. Schematic Representation of a Record of the Time Required to Execute a Sequence of Actions:

A—Time to Execute the Entire Sequence; B_1, B_2 —Time to Execute a Block of Actions; C_1 —Pause Between Blocks; $t_1 - t_2$ —Length of Key Pressing; c_1, c_2 —Pause Between Successive Pressings (the hard transfer-time)—Pause Within Blocks.

Time of Execution of the Entire Sequence of Actions
(Distribution of the A Interval)

In analyzing the time required to complete the series of key-pressing operation in the given order, we attempted to solve the problem as to whether this time is a random variable. To do so, it is necessary first of all to obtain information on the accuracy with which man estimates the time to complete a problem when the time is specified by the experimenter. If we have such information, we can compare the magnitude of the deviation from the prescribed time with the magnitude of the deviations from the average values when the time of completion is not specified.

In the series of experiments carried out by student Kopylova, the group of test subjects was presented the task of learning a sequence of key-pressing actions and of reproducing the sequence from memory. The completion time was prescribed by the experimenter as described above (by means of light signals). With such an experimental setup, the time required to execute the entire series of motions in McGill's light model can be considered as a certain given interval whose fluctuations are a random component (noise) superposed on the regular process. The fixed interval τ (after McGill) is specified either by the experimenter (in this case its values are determined by the distance between the start and stop signals) or is set by the test subject (when its values are determined by the mean completion time). According to McGill, the random component measuring the "noise" relative to the magnitude of the entire cycle is equal to $1/\lambda\tau$, where $\lambda = 1/\sigma$. Thus, the quantity $1/\lambda\tau$ may serve as a criterion for the random component of a certain time interval.

The eight test subjects performing the task were measured for deviations from the interval as fixed by the experimenter. To do so, the tape of the oscillograph which recorded the experimenter's signals and the test subject's actions measured the length between signals from the experimenter and the distance between the work-start signal and the last (24th) key-pressing action. The difference between these values was also calculated. No account was taken of the sign (+ or -) of the deviation. Then $1/\lambda\tau$ was computed for each test subject as

well as the mean $1/\lambda\tau$ for the entire group of test subjects (a total of 168 measurements). In this case the mean $1/\lambda\tau$ was 0.041, which represents the deviations from the fixed interval, if the interval is taken as being the one fixed by the experimenter. It is possible to estimate deviations from a fixed value under the assumption that the interval is set by the test subject himself. In this case the quantity τ will be the mean value of the interval, while $1/\lambda\tau$ will be a measure of the random component relative to the mean value. Calculations made in this way showed that $1/\lambda\tau$ of the individual test subjects has the same values (sometimes a little lower) as for the interval specified by the experimenter.

Given in Table 3 are data for three test subjects. From the data it is evident that the values of τ as measured by the experimenter's signals and by the test subject himself may coincide (test subject G-va), and then the values of $1/\lambda\tau$ also coincide, but when they do not coincide, the $1/\lambda\tau$ are lower for the interval measured by the test subject himself than for that prescribed by the experimenter.

TABLE 3. Fluctuations in the Time it Takes to Complete
A Sequence of Actions Relative to An Interval Specified by the Experimenter and Relative to
A Characteristic Mean

Test subjects	No. of measurements	$\tau_{\text{experi.}}$ (m sec)	$\frac{1}{\lambda\tau}$	$\tau_{\text{charac.}}$ (m sec)	$\frac{1}{\lambda\tau}$
B-va	25	16.750	0.043	17.050	0.035
G-va	25	17.900	0.014	17.900	0.014
S-va	23	19.735	0.037	17.650	0.035

In another series of experiments carried out by student Savilova, the test subjects repeatedly reproduced a learned sequence of 36 key-pressing operations; the time of completion was not prescribed. It was found that in such cases the test subjects themselves limit the time of completion, that is, they set the interval τ .

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Given in Table 4 are data obtained from three test subjects. From the table it is evident that the values of $1/\lambda\tau$ do not exceed those obtained when the time was fixed. Hence it follows that when a human repeatedly reproduces a series of motions, he not only estimates the time of completion with high accuracy, but also marks off this time by a certain, only slightly fluctuating interval.

But these data still do not furnish an answer to the following question: is the time of completion of the entire series of motions a single fixed (prescribed) interval or is the uniformity of the time of completion of a series of motions governed by the presence of rhythmic processes of higher frequency? Isn't this interval the sum of smaller intervals which are also fixed, since we are dealing with discrete motor acts which are similar to each other? This question can be answered by analyzing the distribution of the values of the interval being

TABLE 4. Fluctuations of the Time it Takes to Execute a Sequence of Actions When the Time is Not Fixed

Test subjects	No. of measurements	τ , (msec)	$\frac{1}{\lambda\tau}$
I-va	30	17,000	0,039
B-va.	22	19,450	0,025
K-va.	40	18,800	0,021

considered. Such an analysis of the data we obtained in the different experimental series showed that the distribution of these values does not correspond to the distribution which is representative of McGill's model, which is characterized by the presence of a sharp peak and by a steeper curve. In our case we observed either a sloping asymmetrical distribution, truncated on the left (Fig. 7), or a distribution close to the normal, but truncated on both sides. It is possible that such a pattern is due to sampling which is insufficient for an estimation of the distribution (remember that the maximum number of repetitions of the series of motions did not exceed 100). Later on we intend to repeat these measurements with more statistics. However, the data we obtained are sufficient to determine that the given interval (the time of completion of the entire series of actions) does not correspond to the sharp-peaked distribution typical of McGill's model, and therefore cannot be evaluated as a unit interval fixed by a single pulse (or bounded by two control pulses).

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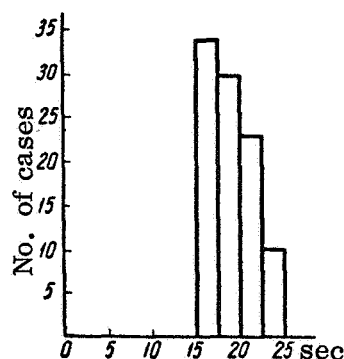


Figure 7. Distribution of the A Interval.

Time of Execution of a Block of Actions (Distribution of the Interval B)

The tasks our test subjects performed were sequences of simple monotonic motions organized in such a way that it was possible to combine several motions into a single complex. In the preceding work we examined these complexes and arrived at the conclusion that they represent a lumping process, and the segment of the sequence containing such a block can be considered as a new complex action consisting of key-pressing and key-to-key hand-transfer operations.

It was assumed that at the higher level of programming the order of the actions, a block of actions is specified as a whole, and is only then turned into a sequence of commands for execution of the individual actions making up the block. In connection with this hypothesis it was only natural to believe that the block of actions is time-ordered. And since the entire sequence consists of blocks and intermediate pauses, and the pauses are not fixed, it follows that the time segments during which these blocks are executed should be uniform and should fluctuate only slightly as compared with the pauses separating the blocks. These arguments were first drawn upon to analyze the construction of final control programs as applied to the speech function [18].

The time organization of the blocks was analyzed on the basis of data obtained from experiments with 9 test subjects. The test subjects learned, and repeated ten times from memory, a sequence of 36 motions made up of 9 blocks of 4 actions each. The time of completion was not prescribed. Since the blocks consisted of an identical number of actions, it was possible to compare data on the time in which the various blocks were completed. It was found that the time of completion of a block of actions by each test subject fluctuates insignificantly within one run of the series of motions as well as from run to run. It was found also that this time is similar for the different test subjects. On the whole, the group of test subjects was subdivided into two subgroups. The members of the first subgroup completed the block of actions in $4,400 \pm 31$ msec ("slow"), while those of the second subgroup did it in $3,030 \pm 34$ msec ("fast"). The value of $1/\lambda\tau$ (0.106 for the first and 0.170 for the second) indicate that the random component plays some small role in forming these intervals. Histograms of the distribution of these intervals are given in Fig. 8. From the figure it is evident that the lengths of the intervals are different for each block, while each subgroup executes a section of the sequence within a slightly fluctuating time interval. However, an estimate of the distribution of the values we obtained did not reveal that it was similar to the distribution of McGill's interval, and therefore we have no reason to evaluate the time expanded in completing a block of actions as the interval limited by two control pulses. On the other hand, our data have shown that this time interval is less random than the interval separating blocks of actions, which confirms the above-mentioned hypothesis on such a structure for the process of ordering actions when the instructions are to execute the entire block of actions. From this hypothesis it follows that the time of execution of a block of actions should fluctuate less than the pause between blocks. Figure 9 shows these relationships.

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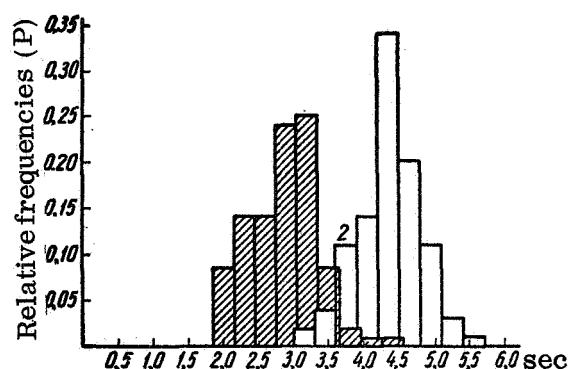


Figure 8. Distribution of the B Interval in the "Fast" (1) and "Slow" (2) Groups of Test Subjects.

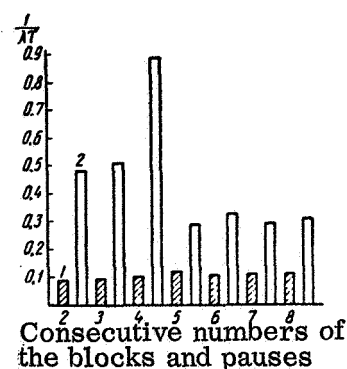


Figure 9. Fluctuations of the Time of Completion of Blocks of Actions (1) in Intergroup Pauses (2) of the "Slow" Test Subjects.

Given in the figure are the values of the random component ($1/\lambda\tau$), characterizing the time of execution of individual blocks of a sequence, and the length of the pauses separating these blocks. From the figure it is evident that the magnitude of the $1/\lambda\tau$ of the pauses is greater by a factor of 3 to 4 than that of the $1/\lambda\tau$ of the time for completion of individual blocks of the sequence. Consequently, the intervals

separating blocks fluctuate strongly. But if each of the separating pauses have a greater random component, and there are 8 such pauses in the entire sequence, the overall error should increase, and the fluctuations of the total time of completion should reflect the sum of the fluctuations of the inter-block pauses, even if fluctuations in completing blocks are neglected. However, as mentioned above, the total time of completion of a sequence is uniform. This may mean that the inter-block pauses are not completely random intervals, but are related in inverse correlation, when strongly reduced pauses after individual blocks are compensated by reduced pauses after other blocks of the sequence. In order to track down this phenomenon, we intercompared the values of the individual pauses between blocks with their total value in the entire sequence. These data are presented in Table 5.

TABLE 5. Fluctuations of Intervals and Their Sum
in the Group of "Slow" Test Subjects

Statistical index	Intervals between blocks							
	2-3	3-4	4-5	5-6	6-7	7-8	8-9	Sum
Arithmetic mean (M), msec	836	1253	992	824	724	851	730	6320
$\frac{1}{\lambda}$, msec	400	636	885	237	229	251	223	1690
$\frac{1}{\lambda\tau}$	0.48	0.51	0.894	0.288	0.315	0.295	0.305	0.27
m, msec	67	106	147	39	38	48	42	280

From these data it is evident that the mean lengths of the pauses between blocks differ from each other and are considerably scattered. But the fluctuation of their sum is somewhat less than might be expected. The magnitude of $1/\lambda\tau$, which characterizes the sum of the inter-block intervals, is less than the $1/\lambda\tau$ of any of these intervals, and the magnitude of $1/\lambda$ of the entire sum is less than the sum of $1/\lambda$ for individual intervals, which could not be true if the random intervals were added together. Thus, there is reason to believe that the inter-block pause, just as the block of actions, is time organized. Before making a decision as to the structure of this organization, let us consider what characterizes the time of completion of a single action in the sequence.

Time of Completion of a Single Action and the Distribution of the Intervals "C," "c"

The time of a single action was measured for various versions of the experiment with the time of completion of the sequence specified and unspecified.

A single action in our experiments can be considered either as the motions of key-pressing or of transfer of the hand to the next key, separately, or the pressing and transfer acts can be considered jointly as a single action, that is, the complete cycle of motions necessary to carry out one action in executing

consecutive key-pressing operations in a definite order. In order to decide which of the time intervals in this case can be considered as specified, the measurement results were analyzed both separately with respect to the pressing time and hand-transfer time, and jointly as the pressing time plus the transfer time. The hand-transfer time, i.e., the pause between two pressing operations, is considered here as applying only to the execution of actions within blocks. The pauses between two pressing operations referring to different blocks (inter-block pauses) were not included in these measurements and are considered separately.

The results we obtained can be reduced to the following principles: 1) the time interval which represents the sum of the pressing and hand-transfer time exhibits less fluctuation than the time segments of which the interval is composed; 2) the distribution of each of the intervals we considered differs from the normal and approaches the distribution of the Laplace function; 3) the magnitude of the random component for each of these intervals does not depend on whether the time of completion of the entire series of motions was prescribed by the experimenter. These principles were illustrated in Figs. 10, A, B, C.

Presented in Fig. 10, A, are the distribution curves for deviations from the arithmetic mean for pressing-time intervals, hand-transfer time intervals, and for total time of the motion (the pressing + transfer times). The curve was constructed from data of a group of test subjects who completed a sequence of 24 key-pressing operations on the panel under specified time conditions (980 cases). From the figure it can be seen that the minimum values of the deviations (that is, of the random component) are found in the summed interval, from which it follows that it is precisely this interval which is the most time-organized.

Shown in Fig. 10, B, is a histogram of the distribution of this summed interval, approximated to the normal distribution. From the figure it is evident that the experimental values of the parameters reveal deviations from the theoretical values. For the normal distribution under the given values of the mean and of σ we should expect a shallower peak and higher "shoulders" than exhibited by the experimental data. On the basis of analogous proofs McGill reaches the conclusion that a regular rhythmic process takes place, and in conformity with his arguments it can be assumed that in our experiments as well the indicated interval is a reflection of a prescribed fixed interval τ , bounded by two control pulses. /55

Shown in Fig. 10, C, is a histogram of the distribution of intervals separating individual motions (the C interval), on the basis of experiments with an unspecified time of completion of the series of motions (4 test subjects, 630 cases). The dashes show the theoretical values, computed under the assumption that the distribution was normal. The differences between the computed and experimental values are the same as in Fig. 10, B.

Thus, it can be assumed that the execution of a series of learned actions by a human being is tied in with the presence of an internal rhythmic process which prescribes a uniform work rhythm. In our case the unit of this rhythm (a period) is the time expended in pressing a key plus the time expended in transferring the hand.

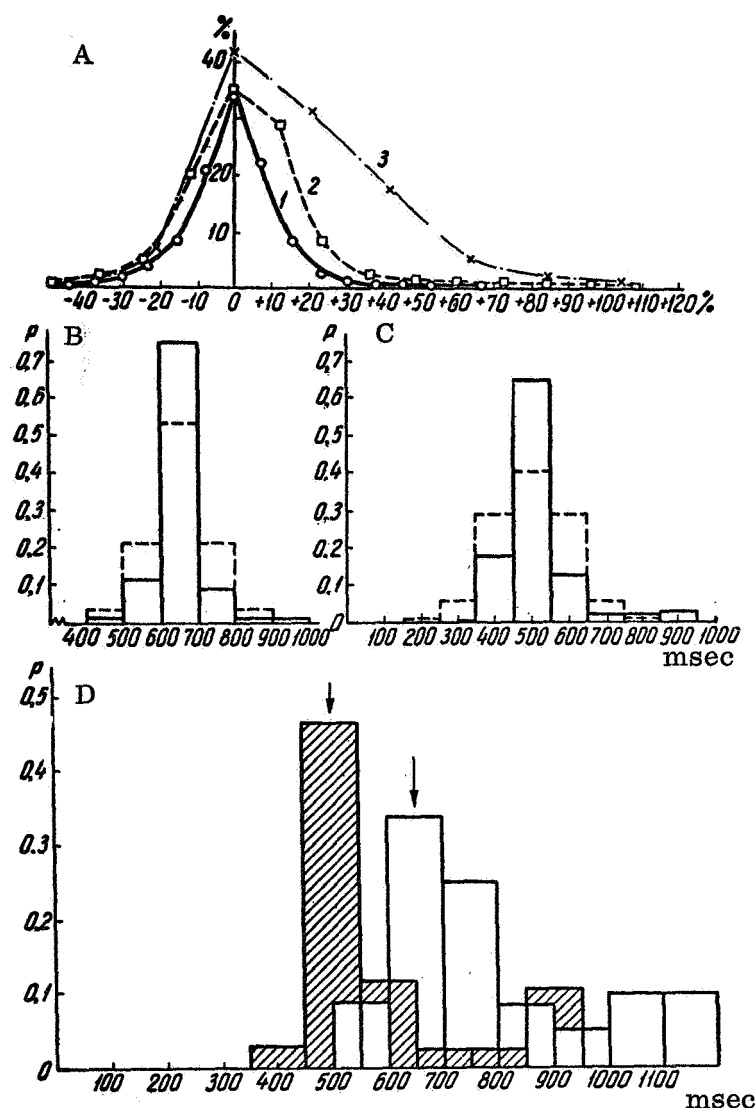


Figure 10. A—Curves of the Distribution of Deviations From the Value of the Arithmetic Mean for the Intervals.

1—Pressing + Hand-Transfer Times; 2—Hand-Transfer Time; 3—Pressing Time. B—Distribution of the Time Interval of One Motion (pressing + hand transfer) and Approximation to the Normal Distribution (dashes). C—Distribution of the "c" Interval and its Approximation to the Normal Distribution (dashes). D—Distribution of the "C" Interval for the Group of "Fast" and "Slow" Test Subjects. The Notation is the Same as in Fig. 8. The Arrows Indicate the Mean Values of the "c" Interval.

Now let us return to the problem of the structure of time organization of the inter-block pauses (the C interval).

Given in Fig. 10,D, are histograms of the distribution of the intervals separating blocks of actions for test subjects with different times of completion of the sequence ("fast" and "slow"). The number of cases was 440. The arrows indicate the mean values of the intervals characterizing the hand-transfer time in executing the actions within a block (the c interval) for each subgroup of test subjects. The figure shows that the peak of the distribution of the C interval coincides with the mean value of the c interval, but the slopes on the right are characteristic of the distribution of inter-block pauses.

In his model McGill considers such a case of functioning of a hypothetical rhythmic mechanism, when the frequency of the control pulses of the rhythm generator is greater than the response frequency. In this case some periods will be "empty," not accompanied by responses. The distribution of the intervals between responses for these cases will have a peak in the area of τ , according to McGill, but should be truncated on the right, while the mean length of the interval will exceed τ .

We believe that the distribution of the C interval is precisely such a case.

Based on the idea that the structure of control of a sequence of actions is hierarchical, it can be imagined that the issuance of instructions to execute a block of actions, which possibly takes place during the inter-block pauses, is somehow tied in with the operation of a higher level of the hierarchy than the issuance of commands to carry out actions within a block. It can be assumed that the operation of a higher hierarchical level is connected with the execution of a large number of operations and requires more time. This circumstance leads to the premise that cases may arise when the next cycle of the rhythmic generator runs "idle," because the processes that ensure the realization of the response had not yet been completed at the instant the pulse was transmitted. In this case the next action is completed not within an interval close to τ , but within an interval close to 2τ , 3τ ,... etc.

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It should be noted that the "tail" of the distribution of the inter-block intervals has a rise approximately in the zone where the c interval is doubled (Fig. 10,D), which favors this assumption.

In previous communications, based on average values and on the assumption of a normal distribution, we presented data showing that the inter-block interval was greater than the other intervals separating individual actions. The analysis made in the present paper has shown that the mean values may not correctly reflect the differences between the inter- and intra-block pauses, since there is no normal distribution here. In conformity with McGill's model it is more correct to assume that in going from one sub-block (block) to the next a "skip" sometimes occurs in the operation of the rhythm generator, and because of this "skip" the histogram of the distribution of inter-block intervals reveals that the distribution slopes on the right, while the average value of the C interval proves to be higher than the value of the c interval. For this same reason, apparently, the quantity $1/\lambda\tau$ also proves to be high.

Conclusion

Returning to the problems posed at the beginning of the article on the processes which ensure the efficiency of human motor skills, we can now attempt to formulate a few answers.

Apparently, fast and accurate execution of a learned sequence of motor acts is based on the organization of the response activity, which is specific for a given sequence (a given motor task). This organization is connected with the formation, during the learning process, of a final control program whose elements are blocks or clusters of individual motor acts, interlinked. The individual motor acts are combined into linked blocks under certain conditions which create the prerequisites for detecting or formulating the structure describing the block of actions as a whole. We partially described these conditions at an earlier date [13]. Among them are the following: 1) the objects for motor acts which are consecutively arranged in the stereotype must be contiguously located in space; 2) one and the same direction of hand displacement must be maintained in executing several motor acts; 3) it must be possible to describe a certain simple figure (a pattern, design, or symbol) by motion of the hand while executing several motor acts. /57

Obviously, the list of conditions we have presented is far from complete; further search and the establishment of new conditions uniting the individual actions into blocks are necessary. On the basis of what is already known, however, it can be assumed that the clustering process is a necessary participant in carrying out a learned sequence of actions.

It is possible that precisely this process is responsible for the high accuracy and speed of execution of a sequence of actions by a trained person, if it is assumed that the consecutive block of actions is completed not on the basis of successive instructions for each action, but of a general instruction to execute the entire group of responses.

Data on numerous transpositions of blocks of actions during the learning process induce us to believe that the nature of the links within blocks differs from that between blocks. The responses within blocks prove to be more closely knit. The time characteristics of stereotypes reveal the essential differences between processes which link motor acts within blocks and those which link blocks of acts to each other. The length of the pauses between individual actions within blocks is considerably smaller than the length of the pauses separating blocks and is characterized by fewer fluctuations. Special computations have shown that this difference cannot be explained by the distance the hand must travel in going from one key-pressing operation to the next.

One of the possible explanations for the difference in time of pause between consecutive actions when these actions make up a block or belong to different blocks is the recognition that there are two processes underlying the combination of actions. One governs the links between actions within a block and the other is associated with connections between the individual blocks of actions making up the stereotype. Further investigations will show what these processes are and how they differ from each other.

Apparently, the blocks of actions we studied can be associated with the presence of partial rules making up the final control program. It is not out of place to mention that there are apparently rules not only for blocking, but also for selection of actions. Analysis of some experiments we made in our laboratory may serve as an illustration of the possibility of such rules [14].

A large group of test subjects (35 people) developed stereotypes of motor acts consisting of successive key-pressing operations on a panel. The test subjects were supposed to establish the order of actions by themselves, since the learning method consisted in a search and guess of each action, the test person being obliged to select one of eight possible keys. In so doing the test subject was permitted to search until he found the necessary response, and the correctness of the response was confirmed by the experimenter. An analysis was made of the errors committed by the test subjects during the learning process so as to determine the nature of his knowledge of the problem and of the order of priority of acquiring individual concrete items of knowledge. Let us consider two types of knowledge with respect to the described task. /58

The first type involves knowledge of concrete responses, i.e., their order in the stereotype. The external expression of this knowledge is a correct response (it is not preceded by a search). The second type involves knowledge with respect to certain abstract properties of the task. For example, in our problems there were no cases in which one and the same actions were repeated in succession (pressing one and the same key). The acquisition of such knowledge by the test subjects is expressed externally not only by the realization of the correct responses, but also by the nature of the errors. The errors will not contain a repetition in succession of one and the same key-pressing operation. In this connection we studied the nature of the errors made by the test subjects after a single familiarization (by searching and guessing) with a given stereotype.

It is natural to expect that people will commit many errors in doing such a problem. Of the 2,352 responses examined, 1,647 were erroneous. We were interested in how many errors are made in repeating the same action. If the test subjects do not know the overall characteristics of the problem, it is only natural to expect that when they decide which actions to take, they will not give preference to any one of the eight possible choices, and the number of errors connected with repetition of any action will be $1/8$ of all the errors, or the expected numbers of errors from a total of 1,647 will be 206. Analysis of our experimental data showed that the second completion of the stereotype resulted in errors stemming from repetition in 28 cases, i.e., $1/59$ of the total number of errors. This means that the test subjects set up or know a rule which limits the repetition of individual responses and divide the set of possible responses into repeating and alternating ones.

Thus, the formation of a final control program is based on a process connected with an evaluation of the sequence of actions to be completed, with the division of the entire set of responses into several subsets, and with the joining of individual responses into blocks having a certain structure by which they can be described as a whole.

The next question which must be examined is the rhythmic and uniform manner in which a sequence of actions is executed. /59

The experiments and calculations we made showed that training of a human being to complete a series of simple homogeneous motions is tied in with rhythmic organization of the execution process. It was found that whether the time of completion of the series of actions was limited from the outsider or whether this time was unlimited, the total time of completion was reduced to a certain slightly fluctuating interval. It was found also that the total time of completion is uniform because the execution of individual parts (blocks) of the sequence of actions was uniform, while the latter is true because the execution of each individual action is uniform. Calculations of the distribution of the various intervals making up the time of completion of a sequence have demonstrated that the most regular interval, and the one closest to McGill's model, is the cycle of one motion (the key-pressing + hand transfer times). The absence of any appreciable difference in the data of the various series of experiments, with the time sometimes being prescribed externally, and sometimes not being prescribed at all, induces us to accept the notion that the rhythms we found are endogenous.

In connection with our data we must discuss several questions. In our previous communications we developed the idea that control of the order of the actions is hierarchical. We expressed the opinion that in executing a learned series of key-pressing actions, there are at least two higher levels of programming the order of the actions; in the upper level instructions are issued to perform a block of actions, followed by a stage in which the block "evolves" and the general instruction is converted into a series of commands to execute individual actions. It is natural to assume that the rhythmic mechanism, whose existence was discussed in the present article, functions at a level which cannot be located higher than the "evolution" level.

One more question must be considered — why is rhythmic organization of a series of actions expedient? Here we can put forth the following two speculative arguments: 1) the rhythms of motor activity we detected are governed by the "internal clocks" of man; 2) rhythmic organization of motion relieves the execution of individual natural motions of the sense of time indefiniteness, thus reducing the load on the mechanisms which evaluate information with respect to its own actions.

No data are available to us on the point where the mechanism which generates motor-activity rhythms is located, although it is natural to assume that it is found in the central nervous system. The problem of the search for such a mechanism is apparently one of the next problems of the physiology of the higher nervous activity.

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ON CERTAIN FEATURES OF PROGRAMMING A SEQUENCE OF HUMAN ACTIONS

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Among the problems to be solved by a pilot-astronaut on board a spacecraft will certainly be those in which individual actions are executed in a definite, rigidly fixed order. The completion of such tasks can be represented by the scheme of an ordered sequence of discrete motor acts. This type of schematic representation makes it possible to investigate certain essential characteristics of the execution process, such as the order of the actions and the distribution of the individual time intervals. The obtaining of information on these characteristics may serve as one of the experimental principles for constructing block diagrams of control of series of motor acts in man, and also to work up tests permitting evaluation of certain aspects of the functioning of a human operator.

In recent years many authors have expressed the idea that human behavior should be considered from the viewpoint of programs which are synthesized in the central nervous system, specifying the actions which are necessary to solve this or that problem [1-4].

If we accept this viewpoint of program control of an ordered sequence of motor acts, we are faced with the problem of the features such a program should possess for a given concrete problem to be solved with certainty with this program.

In the preceding investigation one of us [5] demonstrated that in the process of formation of a sequence of actions by man, an important role is played by a mechanism which combines individual actions into blocks, consistent with the structure of the problem to be solved. This permitted us to postulate that programming a series of actions is tied in with synthesis in the human central nervous system of rules indicating the method by which the individual acts making up the sequence are chosen [6]. In other words, we assume that the control program for a sequence of actions should contain the sum of information on the problem that reflects the essential features of the problem, making it possible to choose the necessary actions from the available set. One such essential feature is the selection, from the sequence, of individual parts (blocks), consisting of several actions, which are linked by a common property. Thus, in the studies we made of sequences of various key-pressing actions on a panel, a description was given of a combination of four consecutive actions which, when executed by a human being, "described" the inverted letter "N" by moving the hand from key to key, or of three actions on contiguous keys, where the hand is moved in one direction, etc. It was found that the majority of people use these features of the problem.

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In the present study we posed the problem of determining to what extent the size of the blocks is a factor governing the structure of a sequence of actions. For this purpose we developed an experimental schedule in which we studied

two ordered sequences of actions which were similar insofar as the set of constituent motor acts and number of elements (length of the sequence) are concerned, but which contained blocks differing in size. By comparing the speed of execution, the error distribution, and the temporal "pattern" of completion of the two sequences by the group of test subjects, we attempted to find out to what extent the feature of the problem being studied is specific and invariant.

METHOD

The experimental arrangement consisted of two relatively small (25 x 30 cm) panels. Arranged on the test subject's panel were 8 signal lights in two rows of four each and 8 keys arranged in the same order. The experimenter's panel contained 8 keys to control the signal lights and 8 monitor lights to observe the actions of the test subject.

The test subjects were persons of both sexes, 18-35 years old, with high school and college education. Two groups of test subjects participated in the experiments. The first group was made up of test persons who were performing this type of task for the first time (12 people). The entire group was taught to perform both tasks until they could be repeated without error. The group was divided into two subgroups of six men each; the order of presentation of the tasks was different in each subgroup. The second group of test subjects (10 people) participated in experiments in which the time of completion of a sequence of actions was measured. This series of experiments was carried out 8 months after the first, and some of the test subjects (7 people) were from the members of the first group. A comparison of the speed of learning problems 1 and 2 was made on the basis of data from the two groups (22 people, 1st and 2nd groups).

The instructions were issued to the test subjects before the beginning of the experiment. These instructions stated that each signal lamp corresponded uniquely to each key on the panel and requested repetition of the order of the actions, which would be shown by the experimenter by means of the signal lights.

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The test subject, who was located in an isolated room, was demonstrated the prescribed order by successive flashing of the respective signal lights on the panel. After each demonstration of the entire series, the test subject repeated what he remembered of the indicated order by pressing the appropriate keys on the panel. This procedure was repeated until the entire sequence was repeated by the test subject completely and error-free. The entire learning process was accomplished during one experiment. Each test subject was presented in turn (with a break of not less than three days) with the two tasks of learning a sequence of actions.

Each problem consisted of a specific series of 36 sequential key-pressing operations on the 8 keys of the panel. If the keys on the panel are numbered 1, 2, 3, 4, the problems can be written as:
5, 6, 7, 8

Problem No. 1 — 2 3 7 6 8 4 7 3 6 5 1 2 8 3 7 2 4 8 7 3 5 6 1 2 5 2 7 4 1 6 3 8 6 3 7 6.

Problem No. 2—7 2 6 7 3 4 1 2 5 2 3 7 8 3 7 1 6 2 7 8 4 2 1 5 3 2 1 7 4 8 6 7 8 2 3 6.

After pressing the first key in the sequence, the test subject was to move his hand and press the next key in order, then move his hand to the third key, etc. If the entire prescribed course is divided into blocks of successive actions, the problems will look as shown in Fig. 1. From the figure it is evident that the order of the actions in the problems was organized in a specific manner. In Problem No. 1 the order was organized in such a way that the entire sequence can be divided into 9 blocks of four actions. The characteristic of each block is that in executing the constituent actions the hand completes a course which, so to speak, depicts a definite geometric figure or pattern (square, zig-zag, triangle, etc.). Problem No. 2 was set up so that it was possible to break it up into 12 sections of 3 actions each.

Thus, the structure of our problems was characterized by the following features:

- 1) consecutive actions in each problem could be combined into blocks of 4 or 3 actions;
- 2) the blocks were organized according to the principle of spatial proximity of the consecutive actions or of the formation of figures;
- 3) all the blocks in one problem were different in configuration, but identical in size.

The essential feature distinguishing one problem from the other was the size of the blocks. On this basis, in what follows we will call Problem No. 1 "four-component" and Problem 2 "three-component."

All the responses of the test subjects, both correct and incorrect, were recorded during the experiments (in report form). In addition, in the experiments with ten test subjects we recorded the entire experiment on the tape of a loop oscillograph. Recorded were the length of the responses (duration of the key-pressing action) and the pauses between responses (the time required to move the hand to the next key) in executing the sequence of actions by the test subjects. The record was made at a tape speed of 4 mm/sec, which permitted measuring the time segments with an accuracy of up to 50 msec when examining the tapes on the photoamplifier.

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RESULTS

Learning and Error Distribution

All repetitions of each sequence by the twelve test subjects were examined with due regard to the number of motions (key-pressing actions) in each run over the entire learning period. The result of this examination is given in Fig. 2, which shows the distribution of the number of motor acts during the learning process. From the figure it is evident that in the majority of cases the test subjects repeat parts of the sequence in segments, where the number of actions is

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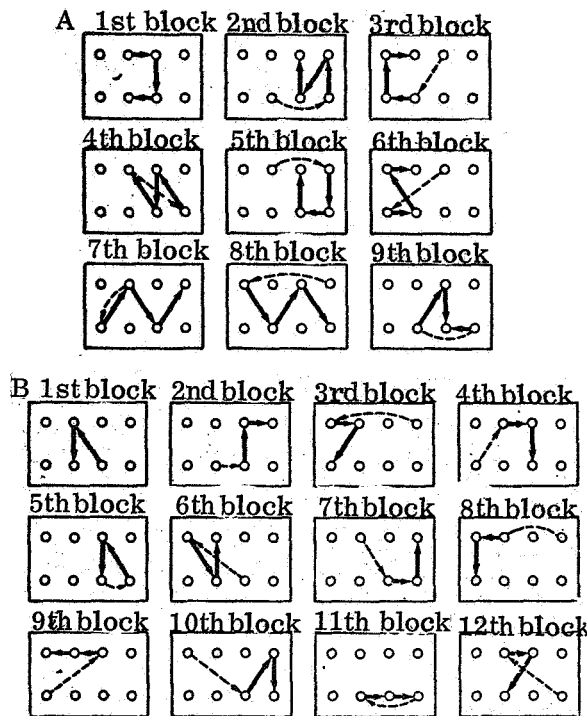


Figure 1. Schematic Illustration of a Possible Division of Problem No. 1(A) and No. 2(B) into Blocks (groups) of Actions. The Solid Arrows Indicate the Order of the Actions Within a Block; the Broken Arrows Indicate the Order of Actions when Passing from the Preceding to the Next Group of Actions.

sequence, or both occurred simultaneously.

Free operation with blocks of actions is clearly evident in analyzing the order of appearance of sequences of correct responses during training. These data are given in Table 2. All possible cases of the order of priority in learning blocks of actions are divided into 3 categories:

- 1) learning of blocks in a sequence consistent with their position in the given series (the first block is learned first, then the second, the third, etc.);
- 2) inverted order of the learned blocks (the seventh, eighth blocks appear before the second, third, etc.);
- 3) other cases of transposition of the order of learning (the third block is learned before the second, the eighth before the sixth, etc.).

The table shows that the learning of blocks in an order consistent with their location in the sequence is observed in 33% of all cases with the four-components

equal to the length of the blocks making up the problem. For the four-component sequence, this was observed in 81% of all cases, and in 75% for the three-component sequence. These data allow us to assume that one of the features of the program of an ordered sequence of actions is sequential clustering into segments of different length for different problems.

Furthermore, we investigated the errors made by the test subjects at the start of training. As is evident from Table 1, the number of errors in the first five trials is considerably greater than the number of correct responses. However, the majority of errors in learning the first as well as the second problem (in evaluating them in connection with the structure of the problems) are not random in nature. As a rule, responses are combined into blocks which correspond to the blocks of the given sequence. In doing so, however, we observed that either the order of actions within a block was distorted, or blocks were misplaced in the se-

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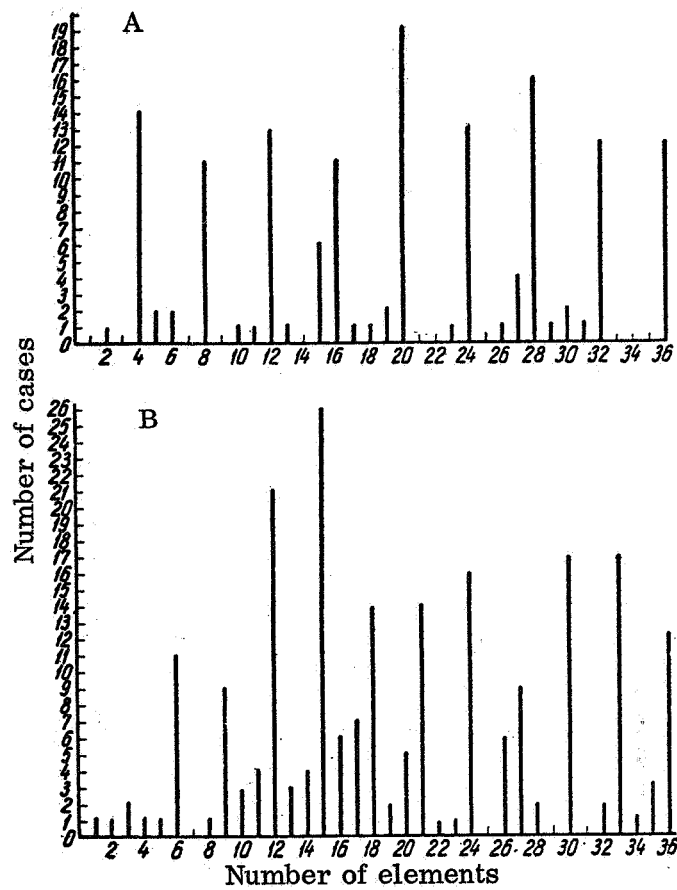


Figure 2. Distribution of the Number of Reproduced Elements in Each Run Over the Entire Learning Period of 12 Test Subjects in Problem No. 1(A) and No. 2(B).

TABLE 1. Distribution of Correct and Incorrect Responses in the First Five Sequences Reproduced

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Number of the problem	Elements repeated	Reponses						
		Correct	Erroneous					Random errors
			Total	Correct blocks mis- placed	Distorted blocks		Incom- pleted blocks	
					in place	not in place		
1	1375	464	911	288	144	200	189	90
2	1203	372	831	201	192	289	—	150

TABLE 2. Distribution of the Order of Learning

Number of the problem	Total number of cases	Blocks of Actions		
		Distribution of the order of learning priority (in %)		
		1st category	2nd category	3rd category
1	117(100%)	33	26	41
2	168(100%)	20	37	43

problem and in 20% of the cases with the three-component one. The large number of transpositions of the order of learning entire blocks indicates that a block of responses is linked by some new unit with which the learning process is involved.

Given in Fig. 3 is an example of how one of the test subjects worked through a four-component sequence. The figure reveals that the order of sequence of the actions is distorted in a number of the blocks, in some cases the order of the correctly reproduced block is broken, some blocks are repeated, the order of priority of learning clusters does not correspond to their position in the stereotype.

On the basis of these data it can be concluded that the basic unit in learning an ordered sequence of actions is a block of actions united by a certain feature. In order to have some justification for assuming that such a block is an element in a control program, it is necessary to have proof as to the execution of the problem after it has been learned.

Time Distribution in Executing a Sequence of Actions

After the 10-man group of test subjects had learned the sequences, ten error-free reproductions from each person were recorded on the tape of the loop oscillograph. It was assumed that if a block of actions is a unit which organizes the rhythmic pattern of the entire sequence, differences between sequences of different blocks lengths should show up in the differing time patterns of the sequences.

To test this hypothesis, we measured the time intervals required to complete a single act, as considered within the framework of its position in the block and in the overall series. First, we computed the total time expended in each execution of the sequence of actions. For further analysis we chose 84 cases of completion of Problem No. 1 (9 test subjects) and 57 cases of completion of Problem No. 2 (6 test subjects). The selection principle was governed by the uniformity of the work of the test subjects; excluded were experiments in which the time difference between separate executions of the task (by the given test subject) exceeded 10 sec. We counted 588 blocks from the four-component sequence and 570 from the three-component one. The time pattern of each block was described by the following measurements:

For the four-component sequence (Problem No. 1):

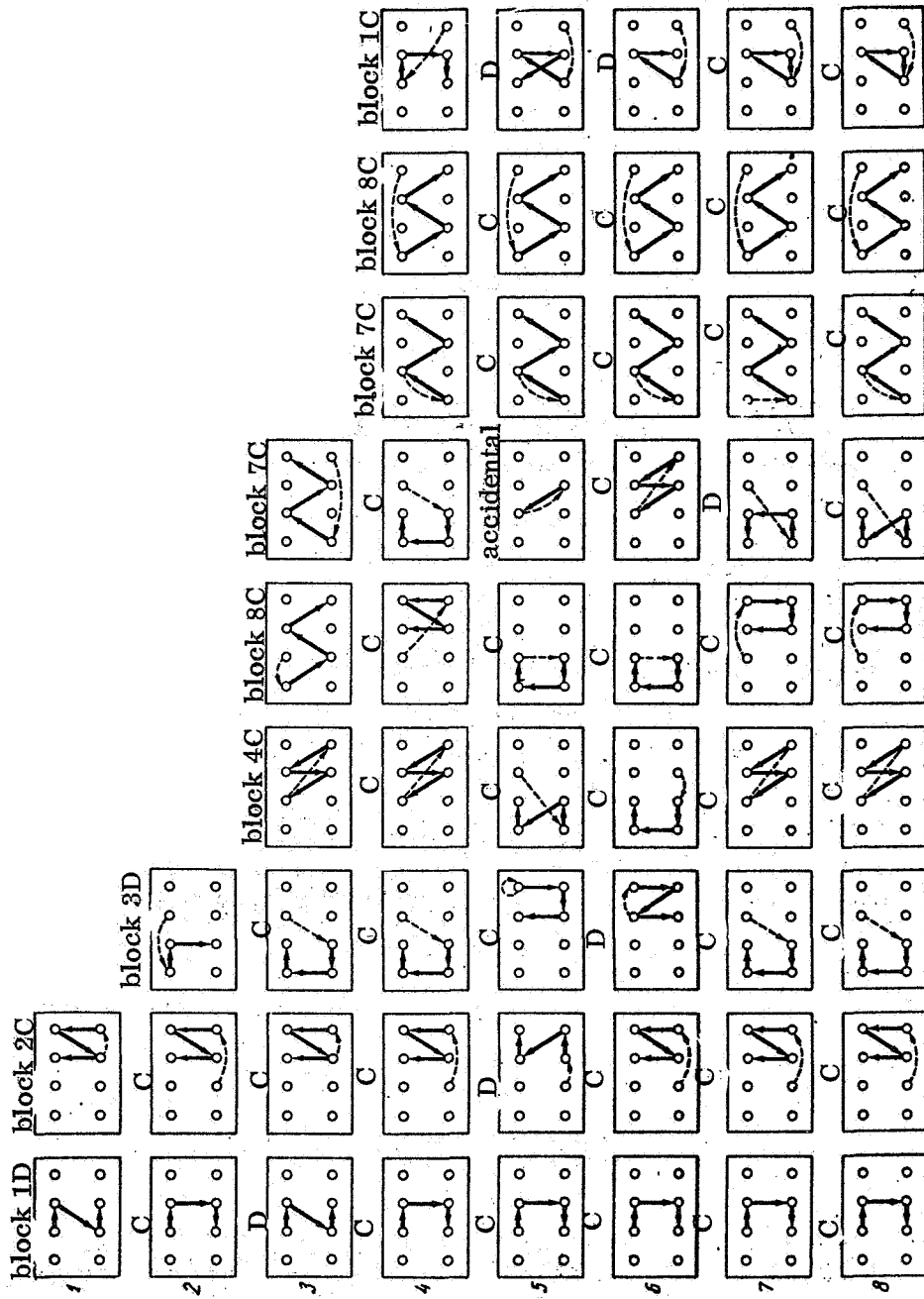


Figure 3. Reproduction by Test Subject E-v of a Sequence of Actions in Each "Step" of the Process of Learning Problem No. 1. The Figures on the Left are the Consecutive Numbers of the "Steps"; C is a Correct Block, D a Distorted Block of Actions. The Remaining Notation is As in Fig. 1.

1) the duration of the 1st motion in the block (the key-pressing time); 2) the duration of the pause between the 1st and 2nd motions; 3) the duration of the 2nd motion; 4) the pause between the 2nd and 3rd motions; 5) the duration of the 3rd motion; 6) the pause between the 3rd and 4th motions; 7) the duration of the 4th motion; 8) the pause between the 4th motion of the given block and the 1st motion of the next block (the inter-block pause).

The distribution of time intervals within the blocks of the three-component sequence was described in the same manner. In our computation the parameters measured for the various blocks of one problem were averaged and plotted in the form of a distribution within one "average" block. Then we calculated the mean deviations (x), the root mean square deviations (σ), and the errors of the mean (S) for each interval. The averaged data are given in Table 3.

TABLE 3. Distribution of Time Intervals in the Completion of Blocks of Actions in Problems Nos. 1 and 2

Parameters	Statistical index	Problem 1					Problem 2			
		Successive positions in the block				difference	Successive positions in the block			difference
		1	2	3	4		1	2	3	
Duration of the motions (msec)	x	460	440	490	450	30	450	410	480	
	σ	194	145	218	146		167	143	238	
	S	8	6	9	6		7	6	10	
Pauses between motions (msec)	x	580	590	600	860	260	650	610	880	230
	σ	218	170	121	655		476	238	668	
	S	9	7	5	27		20	10	28	

Remark: The semi-boldface numbers denote the values of the intervals for which a comparison was made between the significance of the differences. The corresponding values of the difference are entered in the "difference" column. In all cases the magnitude of the differences is considerable ($P < 0.01$).

As is evident from the table, the time pattern of the blocks of each problem has its own characteristic features. In the four-component blocks of Problem No. 1, the pause that corresponds to the position between blocks is considerably longer than the other pauses that separate individual motions within blocks. The same relations between intra- and inter-block pauses are observed in the blocks of Problem No. 2; here the pause separating the three-component blocks of the problem proves to be longer.

Also deserving of attention is the considerable increase in the standard rms deviations (σ) of the inter-block pauses as compared with the intra-block pauses. Given in Table 4 are the frequency characteristics of the distribution for the values of the inter- and intra-block pauses in Problem No. 1.

TABLE 4. Frequency Characteristics of the Distribution of the Value of the Intra- and Inter-block Pauses in Executing Problem No. 1

Length of the pauses (msec)	Relative frequency of occurrence (%)	
	intra-block	inter-block
300—450	15	5
500—650	68	51
700—850	14	21
900—1050	1	6
1100 plus	2	17

This characteristic of the distribution of the values of the intervals we examined demonstrates that the peak of the distribution for the intra-block as well as inter-block pauses is found in a single region; the mean value of the inter-block pause increases because of the large scatter in the values of the inter-block pauses and because of the considerable number of cases in which the magnitude of these pauses is approximately double the mean value of the intra-block pauses (at a mean value of 590 msec for the intra-block pause, the number of cases in which the inter-block pause exceeds 1100 msec is 17%).

From Table 3 it is also evident that the time pattern of the problems differs also in the duration of the individual motions as a function of their location within the block. Thus, in Problem No. 1 the third motion is certainly longer than all the other motions.

Thus, the time characteristics of execution of a sequence of actions seem to favor the argument that the basic unit of a control program is a block of actions whose size is governed by the presence of a common feature that permits description of the block as a whole.

Comparative Learning Speeds

According to the literature data, the learning speed for a sequence of symbols is linearly related to the number of learned elements [7]. A similar relation was found by Bogina [6] for the case of learning a sequence of actions.

On the basis of these data we postulated that if a block of actions, and not a single motor act, is an element of the program, then the four-component sequence containing 9 blocks should be learned faster than the three-component sequence consisting of 12 blocks.

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Given in Fig. 5 are the total data on the speed of learning of a sequence of actions. As the learning-speed criterion we took the number of demonstrations and repetitions of the sequence until the first error-free completion.

The table shows that Problem No. 1, which consists of 9 blocks of 4 actions each, is learned faster than Problem No. 2, which consists of 12 blocks (of 3

TABLE 5. Speed of Learning of a Sequence of Actions

Name of test subject	First experiment (Problem No. 1)	Second experiment (Problem No. 2)	Name of test subject	First Experiment (Problem No. 2)	Second Experiment (Problem No. 1)
1st group of test subjects			2nd group of test subjects*		
B-v...	23	25	B-va...	16	7
I-v...	25	39	E-v....	10	8
M-va..	16	20	E-v....	12	3
M-va..	10	23	Z-o....	12	7
P-va..	14	12	K-va	27	9
P-va..	14	12	L-va	19	8
P-v A..	9	11	L-va	17	10
P-vYu.	13	14	M-o	19	12
P-vYu.	9	19	M-o...	12	10
F-va...	10	15	N-v...	26	11
F-va...	6	15	R-ya..	9	6
Average speed	13.5	18.6	Average speed	16.3	8.3

actions each). The significance of these differences was evaluated by Wilcoxon's nonparametric criterion ($P < 0.05$).

CONCLUSION

In formulating the problem of the present investigation, we suggested that the formation of an ordered sequence of actions is connected with the process of grouping individual motor acts, and we attempted to demonstrate that the presence of blocks (groups) and their size are factors which determine the structure of the given sequence. We examined the effect of these factors on the character of learning and executing two sequences of equal length (in number of motor acts), but different in the structure representative of the block.

The course of the learning process can be described by the growing number of learned acts and by the order in which they are learned relative to their position in the sequence. This characteristic can be observed in an especially convenient manner by a learning method in which the test subject himself, freely reproducing a prescribed sequence of actions, controls both the number of motions and their order of sequence.

The results of the investigation have shown that in learning each sequence the accretion and order of learning material reveals general features which are connected with the presence of the grouping process and differences which are due to the specific properties of the group (block). That the learning process has general features is manifested in the nonuniformity of accretion; rather it is stepped in nature, in that not a single motor act is added, but an entire block. The order of learning did not correspond to the order of the individual acts in

the sequence. The order of the motor acts in the block and the location of the blocks was learned separately. On the basis of these data it can be assumed that two independent processes, forming an organized sequence of learned acts, participate in learning: the process of combining single acts into blocks and the process of combining blocks. The differences in learning two sequences are due to the size of the blocks of motor acts and to the number of these blocks. In Fig. 2, which shows the distribution of the number of reproduced motor acts, it is clearly evident that the largest number of cases in Problem No. 1 relates to the reproduction of 4, 8, 12, 16, ... motor acts. In Problem No. 2 the most frequent cases are those in which 6, 9, 12, 15, ... motor acts are reproduced. This means that the magnitude of the increment is dependent on a grouping process, which is connected with the specific structure of each problem.

The differences stemming from the different number of blocks in the problems are revealed in the differing learning speeds. Our data show that a sequence containing a smaller number of blocks of greater size (Problem No. 1) is learned at a distinctly greater speed. Evidently, this indicates that grouping into sufficiently large blocks facilitates learning.

Analysis of the distribution of time required to complete a sequence of actions showed that the grouping process is connected not only with learning. Of greatest interest to us are the results of measuring the magnitude of the pauses between consecutive actions. These results indicate that the pauses between two consecutive actions are different, depending on whether these actions are a part of the same block or of two successive blocks. Inter-block pauses are substantially greater than intra-block pauses; in Problem 1 the difference between them was ≥ 260 msec, and in Problem No. 2, ≥ 230 msec. Obviously, this difference in time is tied in with such characteristics of the problems as the presence of blocks.

One of the possible explanations for the greater length of the inter-block pause is that the time it takes to move the hand over the panel differs because of a certain difference in distance between separate keys.

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If we return to Fig. 1, where the possible grouping of responses in the problems is shown schematically, it can be observed that the distance the hand has to travel from one key to the next is not the same in all cases. It turns out that hand transfer over the smaller distances is more frequently equivalent to the execution of consecutive actions comprising a single block (the solid arrows) than in transfers from one block to the next.

The second explanation is related to the idea that the structure of the control program is hierarchical, so that the issuance of instructions to execute a block of actions requires a larger number of operations to be completed than instructions to execute individual actions within a block. Such an assumption naturally implies that there is a difference between intra- and inter-block intervals.

We can decide which of these explanations is the real one by measuring the length of the pauses in those segments of the problem in which intra- and inter-block pauses are equivalent to hand transfer over equal distances. Such a segment can be found in Problem No. 1 (Fig. 1). In the transition from block No. 6 to block No. 7, it is necessary to move the hand from key 2 to key 5 (the hand-transfer time in this case is denoted as the inter-block pause); the first intra-block

pause in block No. 7 relates to hand transfer in the opposite direction, from key 5 to key 2, that is, over the same distance. If the first hypothesis is correct, and the difference in magnitude of the inter- and intra-block pauses is actually due to the difference in distances, in the given segment of the sequence there can be no difference in the magnitude of the pauses. But if the second hypothesis is correct, the difference in time should hold.

We made measurements and pairwise comparisons of 190 such intervals for the entire group of test subjects. It turned out that, despite the absence of a difference in distance in moving the hand, the inter-block pause (transfer from key 2 to key 5) exceeds the intra-block pause (transfer from key 5 to key 2) by 258 ± 67.5 msec. This means that the difference in length of the inter- and intra-block pauses is not connected with the hand-transfer time and the distances, but is a characteristic of the control program.

The problem of the nonuniformity in the time of completion of the motor acts themselves (the duration of the key-pressing action) as a function of their position in the block is disputable. It was shown above that in blocks of the four-component sequence, the next to last (third) action proves to be somewhat extended in time, which may be due to the distribution of control commands of the program. It may signify that at this instant preparations begin to execute the next block of actions. The likelihood of such a hypothesis is supported by the fact that in executing the sequence the last block did not reveal a longer third action, as can be seen in Table 6, which shows the averaged data from 86 cases of completion of the block.

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TABLE 6. Average Duration of Motions in Executing the Last Block of Actions in the Four-Component Sequence (in msec)

Statistical index	Sequential locations of the motions in the block			
	1	2	3	4
$\bar{x}$	460	400	460	460
S	14	10	14	17

But these ideas remain speculative, and this question is in need of further experimental study.

The results obtained in these experiments demonstrate that the time distribution over intervals of completion of a certain motor problem is invariant. This fact makes it possible to set up various test problems with a completely predicted time pattern of execution. This means that such problems are completely suited for evaluation and description of certain aspects of the work of an operator, such as monitoring a sequence of actions. Obviously, the next step in developing such problems as tests is their use under spaceflight simulation conditions.

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NERVE CONTROL OF THE TEMPO OF MOTION IN MAN
AND POSSIBLE METHODS OF REPRESENTING
TIME IN THE NERVOUS SYSTEM

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N. A. Rokotova

One of the central questions of the problem of perceiving time has long been the question of methods of describing time in the nervous system.

We can select three aspects under which this question is considered. The first is connected with the idea that time perception does not exist in a void, but is connected with measurement of the duration of events, of pauses between individual events, that is, it is connected with the perception of certain signals [3, 5, 11].

The second aspect of consideration deals with representation of subjective time stemming from the characteristics of active processes taking place in the organism. This question has been studied in greatest detail by Bünning [2] insofar as it applies to time intervals which record days, as well as by many researchers insofar as it concerns the interval of 0.6-0.7 sec, which has received the name of "neutral" interval in the literature [3]. In recent years the viewpoint has taken hold that an active part is taken in time measurement in the nervous system not only by vegetative rhythmic processes, but also by an ordered motor system [5, 6]. The third aspect of the question of time representation in the nervous system relates to the search for physiological time counting units. The intense long-standing attention of psychologists to the "neutral" interval is, without doubt, somehow connected with the desire to find a certain subjective time-counting unit in this interval.

But investigations of the "neutral" interval have not lead to distinct and uniform results, the reasons for which have been thoroughly analyzed by Woodrow. To the analysis made by him we might add the absence of clear theoretical ideas on the part of investigators of the "neutral" interval and the absence of attempts to tie in "psychological" time with somatic motor activity.

The first attempt to establish a theory on the representation of time intervals in the nervous system is due to McGill [10], who described a model of an interval generator and considered some applications of this model. The main point of McGill's theory is the idea of the existence of an active nervous mechanism which generates pulses of a rigorously defined frequency and participates in control of the time characteristics of motion.

Although McGill does not examine the neurophysiological foundations for such a mechanism, it should be noted that his theory could be supported by such foundations. Thus, e.g., Eccles, Leinas and Sasaki [9] in 1966 published data on the existence, in the cerebellum, of neurons, whose function is to generate rhythmic discharges of a specific frequency. Similar data have been published by Breitenberg [8].

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In our paper [4] we demonstrated that man, in executing a consecutive series of motions with his hands, choosing his tempo independently, works so uniformly that the distribution of intervals during which individual motor cycles are executed agree well with McGill's model.

On the basis of these data we formulated the hypothesis that a uniform work tempo is maintained by virtue of the functioning of a nervous mechanism which generates intervals of fixed frequency, the effector system being turned to this frequency.

Subsequent research convinced us that this hypothesis is in need of being supplemented. Experiments have shown that there exists not a single tempo which can be maintained with high precision. This means that the mechanisms which generate intervals may contain certain sets of intervals which differ from each other. If this is true, then it is possible that there exists a step-type mechanism, as described by Ashby [7], which changes control of the tempo of motion from one value of the generated interval to some other. It is natural to believe that time description in the nervous system may be connected with a set of intervals used to control the tempo of motion.

The problem of our present investigation reduced to a clarification of the problem of the number of different possible speeds of execution by a human being of certain motor activity, of the level of precision with which each of these speeds is maintained, and of the relations between the speed-maintenance function and the function of transition from one speed to another.

We studied the motions of the hand in performing a fixed series of successive key-pressing operations. In the experiments, in which 3 persons participated, we measured the magnitude of the interval during which a motor cycle was completed (t_{mot}) and the length of the total interval (t_0) in which the same fixed sequence of motions was completed.

The problem of the test subject consisted in learning a distinct path of hand motion over the experimental panel while executing 24 button-pressing operations on the panel. After being trained we started the basic series of experiments, during which the test subject repeatedly reproduced the learned sequence, successively changing arbitrarily chosen speeds from the fastest to the slowest.

The structure of the order of the motions made in executing the indicated sequence of actions has the following features.

1. Three consecutive pressing operations in the sequence (1-3, 4-6, ..., 21-24) are completed moving the hand in the same direction over the panel.

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2. Each succeeding triad differs from the preceding by a change in direction of hand motion. The different directions are: right, left, clockwise, counterclockwise, diagonally right and diagonally left.

The results of our previous research had shown that the time characteristics in executing such a sequence can be predicted. The time interval during which the triad motor cycle is completed fluctuates but little, and its distribution indicates

specificity [4]. The interval between triads has a more random nature; it is characterized by high dispersion and an asymmetric distribution.

Time of a Motor Cycle While Maintaining and Changing Work Speeds

The instruction prior to beginning the experiment directed the test subject to:

- a) choose the fastest speed and repeatedly execute the sequence while adhering to this speed;
- b) change the speed by slowing it to the lowest possible value and repeatedly execute the sequence while adhering to this new speed;
- c) repeat instruction (b) with regard to the second speed and other speeds. The experiment is terminated after the test subject states that it is difficult or impossible to choose a slower speed.

The results of measuring intervals characterizing the time of completion of a single motor cycle (moving the hand + pressing) are given in Table 1; they show that:

- 1) each speed chosen by the test subject is related to a stable value of t_{mot} . The dispersion of the values of t_{mot} does not exceed a certain limit;
- 2) a change in speed is connected with a change in t_{mot} by a value greater than the magnitude of the dispersion.

The results we obtained indicate the presence, in the nervous system, of a set of intervals, and, in conformity with these intervals, the time of completion aspect is the selection of an interval from the set and turning to it. The degree of stability of the speed can be described as a measure of the deviations from the mean value of $t_{mot}(\sigma t_{mot}/t_{mot})$. In analyzing the stability, we found that it was a function of the interval $t_{mot}(\sigma t_{mot}/t_{mot} = \text{const})$. These relations are evident in Table 1.

Similar results were obtained in the work of I. N. Krylov and from the laboratory of M. A. Alekseyev from test subjects tapping a keyboard with his fingers (private communication).

The maintenance of a single tempo and changeover to a different tempo, maintaining the second tempo, and the characteristics of t_{mot} obtained in doing so, agree with Ashby's ideas on two brain control mechanisms [7].

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The first mechanism is designed to maintain the control variable within certain given limits. The operation of such a kind of mechanism ensures that the t_{mot} interval is maintained at the level of the given tempo. Then fluctuations of the interval show the limits of the field of the variable and are a real part of the description of the operation of the given mechanism.

The second mechanism illustrated in Ashby's theory, which he called a step function, is designed to transfer the values of the variable from one field to another. The operation of this kind of mechanism can ensure the change in t_{mot} values detected in the experiments. Then the measure of the difference between the values of $t_{\text{mot}n}$ and $t_{\text{mot}n-1}$ is essential for a description of the step mechanism. Under conditions of our experiments, when the test subject is instructed to change the tempo to the minimum possible value, a certain threshold value was prescribed for the step function, ΔT .

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TABLE 1. Length t_{mot} and Fluctuations σt_{mot} in Executing a Motor Cycle While Maintaining Each of the Chosen Speeds (the Mean Number of Measurements of Each Quantity 70 ± 3)

No. of speed	P-v			G-va			R-va		
	t_{mot} , msec	σt_{mot} , msec	ΔT^* , msec	t_{mot} , msec	σt_{mot} , msec	ΔT^* , msec	t_{mot} , msec	σt_{mot} , msec	ΔT^* , msec
1	250	20		325	33		285	33	
2	280	23	30	360	34	35	340	29	55
3	310	21	30	400	30	40	430	30	90
4	340	24	30	475	55	75	520	36	90
5	370	28	30	545	42	70	660	40	140
6	410	24	40	645	46	100	970	44	310
7	450	35	40	740	62	95	1240	61	270
8	500	39	50	835	83	95			
9	570	37	70	1010	68	175			
10	630	55	60	1150	80	140			
11	710	48	80	1335	130	185			
12	770	59	60						
13	850	77	80						
14	1060	85	210						
15	1250	83	190						

* $P(\Delta T > \sigma t_{\text{mot}}) = 0.999$.

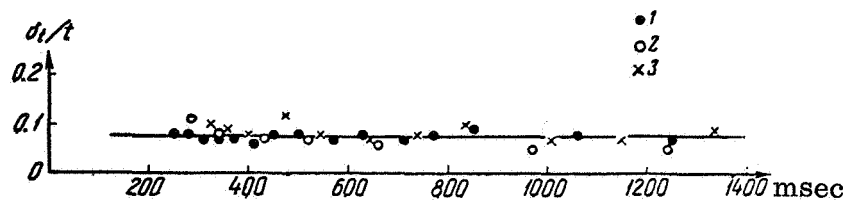


Figure 1. Dependence of $\sigma t_{\text{mot}}/t_{\text{mot}}$ on the Magnitude of t_{mot} at Various, Arbitrarily Chosen Speeds: 1-2-3, First, Second and Third Test Subjects.

Further analysis of ΔT showed that it depended on the magnitude of t_{mot} , but this relation is of a different nature as compared with the interval-maintenance function. The interval grows on a logarithmic scale, whereas the test subject assumes that it provides a uniform minimum increment to the value of t_{mot} .

The values of t_{mot} with work speeds chosen successively by the test subjects are plotted in a logarithmic scale in Fig. 2. From the figure it is evident that the individual points are arranged fairly well in a straight line, the slope of which describes the step function of the given test subject,

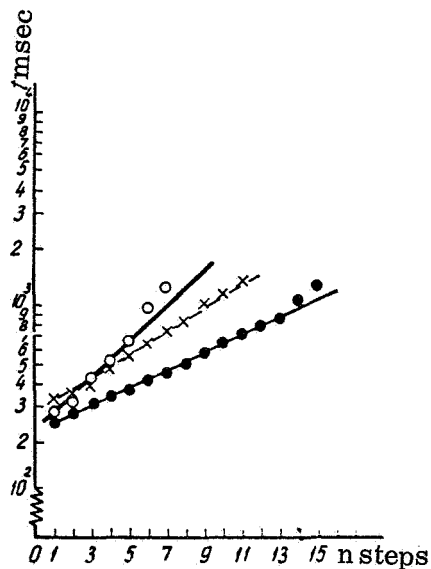


Figure 2. Magnitude of the Intervals of Motor Cycles in the Case of Consecutively Chosen Work Speeds in the Part of the Test Subjects. The Notation is the Same as in Fig. 1.

For the completeness of the characteristics of the two functions it is necessary to say that the number (set) of work speeds for the same test subject fluctuates somewhat in the different experiments, having a tendency to increase with training. Test subject G-va revealed 7 gradations in speed in the first experiment and 11 in the second, R-va revealed 6 gradations in the first experiment and 7 in the second. At the same time it is completely possible that there are a certain number of speeds which describe the individual traits of the test subject. The study of these traits in various people is highly rewarding for purpose of applied psychology.

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Time of Completion of a Fixed Sequence of Motions While Maintaining and Changing Speeds

The total time of completion of a sequence (t_0) while maintaining and changing work speeds is shown in Table 2.

From the table it is evident that while maintaining each speed the interval is very stable, the error in speed precision ($\sigma t_0/t_0$) not exceeding 0.05.

There is also a certain difference between two adjacent intervals ΔT_0 , which exceeds the error in precision.

Shown in Fig. 3 are values of t_0 for test subject P-va over the entire range of selected work speeds. From the figure we can see both the characteristics of holding t_0 precise, expressed as rms deviations, as well as values relating to ΔT_0 , representing differences between two adjacent t_0 .

TABLE 2. Total Time of Completion t_o in the Case of Arbitrarily Selected Work Speeds

No. of work speed	P-v			G-va			R-va		
	t_o , msec	$\frac{\sigma_{t_o}}{t_o}$	ΔT_o^{**} , msec	t_o , msec	$\frac{\sigma_{t_o}}{t_o}$	ΔT_o^{**} , msec	t_o , msec	$\frac{\sigma_{t_o}}{t_o}$	ΔT_o^{**} , msec
1	6000	0.020		7850	0.029		6840	0.021	
2	6650	0.009	650	8600	0.018	750	8160	0.013	1320
3	7470	0.026	820	9680	0.026	1080	9980	0.017	1820
4	8030	0.018	560 *	11330	0.046	1650	12130	0.018	2150
5	8970	0.014	940	12940	0.007	1610	15450	0.019	3320
6	9920	0.011	950	15490	0.019	2550	22620	0.003	7170
7	10920	0.020	1000	17580	0.031	2090	28850	0.010	6230
8	11960	0.019	1040	19900	0.056	2320 *			
9	13550	0.024	1590	23770	0.012	3870			
10	15010	0.032	1460 *	26980	0.019	3210			
11	16760	0.026	1750 *	31640	0.023	4660			
12	18530	0.015	1770						
13	20030	0.023	1500 *						
14	25240	0.029	5210						
15	30030	0.006	4790						

* $P(\Delta T_o > \sigma_{t_o}) = 0.99$.

** $P(\Delta T_o > \sigma_{t_o}) = 0.999$.

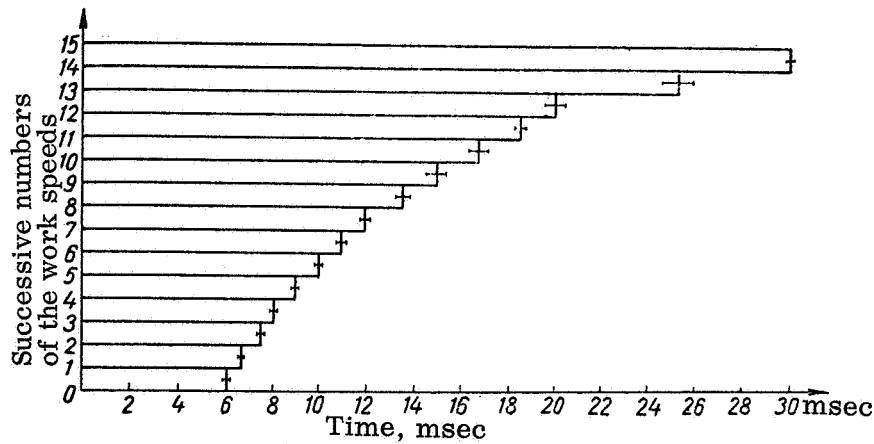


Figure 3. Total Time of Completion of the Problem (t_o) by Test Subject P-va in the Case of Arbitrarily Chosen Work Speeds. The Errors Indicate σ_t .

Now let us go on the relations between t_o and t_{mot} . Figure 4 presents the interval t_o as a function of t_{mot} , revealing that $t_o = a + kt_{mot}$. Since the interval t_o is a derivative of t_{mot} , it is clear that the characteristics of the functions

representing maintenance of the interval and of the step function are preserved. Here we are faced with the question of the complications in uniform maintenance of the work speed that arise in connection with the conditions of the problem (with the order of the actions in the sequence). Earlier it was demonstrated that sequences consisting of individual organized blocks are described, with respect to time characteristics, by more precise intervals for motions forming a block and by less precise intervals at points separating blocks.

In one of the articles it was shown that the peak of the distribution of these inter-block intervals coincides with the peak of the distribution for intra-block intervals, but the sharp slope of the distribution to the right is responsible for the greater average values of these intervals. In conformity with McGill's model, we consider control of these intervals as control with an error, where there is a probability that jumps or idle cycles of the generator occur. The given sequence contains not less than 3 such separating intervals. At the same time, the interval t_0 behaves as if these intervals did not exist. One of the possible explanations of this fact may be that organization of t_0 on the level where a decision is made as to the choice of the number of pulses from the rhythm generator is somehow connected with allowance being made for the probability of idle generator cycles.

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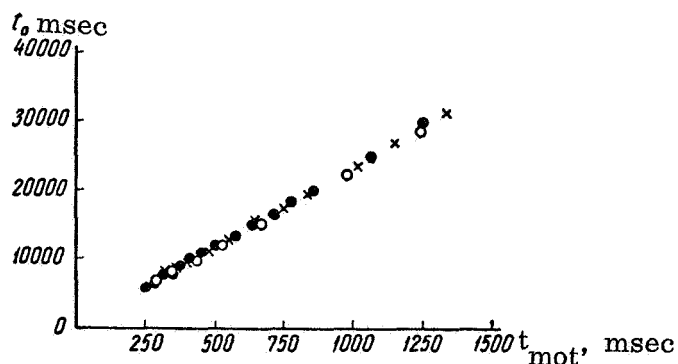


Figure 4. Total Time of Completion of a Problem as a Function of the Length of the Motor Cycle. The Notations 1, 2 and 3 are the same as in Fig. 1.

If it is assumed that this probability does not vary, we can imagine that to execute a sequence a greater number of rhythmic control pulses is needed than there are motions. We suggested that under the given conditions, with a number of motions $n = 23$ (this many motor cycles can be measured for a sequence of 24 motions), the number of control pulses is $n + 1$ with an interval between two pulses of $\tau = t_{mot}$.

Given in Table 3 are the values to which t_0 should correspond under this condition, and the values actually found experimentally.

In this case we assumed that agreement between the calculated and experimental t_0 can be considered sufficient if the difference between them does not exceed the rms deviation. As evident from the table, where the values representative of the activity of test subject P-va are given, agreement between the theoretical and experimental t_0 intervals was observed in 14 out of 15 cases. The same was observed with the other test subjects. Thus, the hypothesis that the total time of completion of a problem is organized by fixing the number of generated intervals with allowance for errors in execution is not without foundation.

However, if control of the interval t_o is so rigorously dependent on the number of rhythmic pulses, the error in execution should obviously lie within the limits of a single pulse. And this means that σt_o should be $\leq t_{mot}$. The equivalent data are shown in Table 3, from which it is evident that this relation is valid in all cases.

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It is very important to emphasize that the described precision of t_o and the simplicity of calculating it are not in direct relationship with the values of the intervals t_{mot} . If we return to a consideration of the rhythmic structure of a sequence, we can see that the average values of t_{mot} for the intervals of motions making up a block are not equal to the intervals which separate consecutive blocks. Hence, all the intervals of motions making up a block are always selected for t_{mot} . As has already been mentioned, the average values of the inter-block intervals are always greater than the corresponding t_{mot} . Thus, the lengths of these two types of intervals can serve as evidence for the rhythmic structure of the sequence (although, as we already wrote, the difference between the average values does not completely reflect the nature of the differences between these intervals).

TABLE 3. Relations Between the Theoretical and Experimental Values of t_o , and Also Between Their Differences, t_{mot} and σt_o , for Test Subject P-v

No. of the work speed	t_{mot} msec	Computed value of t_o ($t_{mot} \times 24$)	Experimental value of t_o	$\Delta(t_o \text{ theor. to experi.})$ msec	σt_o msec	$\sigma t_o > \Delta$	$t_{mot} > \sigma t_o$
1	250	6000	6000	0	123	+	+
2	280	6720	6650	70	58	-	-
3	310	7440	7470	30	198	+	+
4	340	8160	8030	130	142	+	+
5	370	8880	8970	90	128	+	+
6	410	9840	9920	80	110	+	+
7	450	10800	10920	120	224	+	+
8	500	12000	11960	40	226	+	+
9	570	13680	13550	130	327	+	+
10	630	15120	15010	110	491	+	+
11	710	17040	16760	280	430	+	+
12	770	18480	18530	50	276	+	+
13	850	20400	20030	370	470	+	+
14	1060	25440	25420	20	729	+	+
15	1250	30000	30030	30	177	+	+

Shown in Fig. 5 are data of the experiment with test subject P-v. The hachured columns are the length of the intervals for motions during the transition

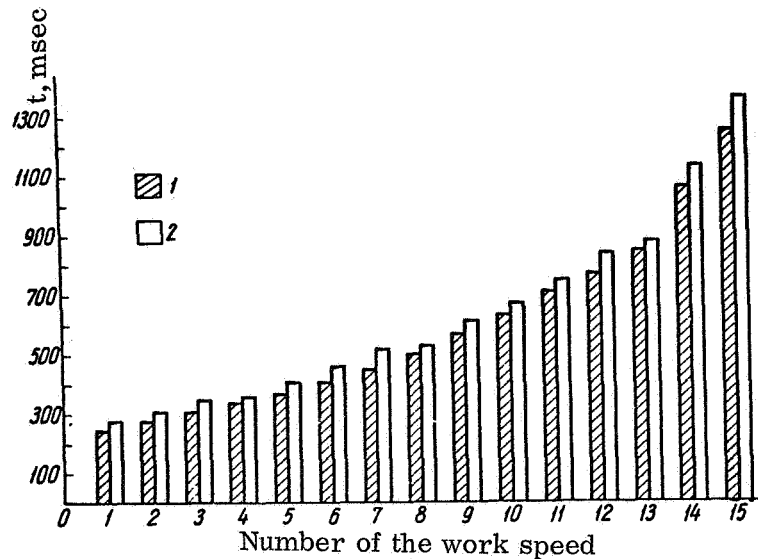


Figure 5. Length of t_{mot} (1) and of the Intervals Separating Organized Blocks (2) at Different Work Speeds for One Test Subject.

from one block to the next for all 15 work speeds. Distinctly evident is the invariant rhythmic structure of the sequence, which we have already described, the control of which is independent of the control of the tempo of work.

CONCLUSION

The experimentally obtained data demonstrate the high precision with which time intervals are repeatedly reproduced in motor activity when the work speed is freely chosen. It turned out that the precision of the intervals for completion of a single motion (t_{mot}) within the limits of 250 to 1250 msec, as described by the relative error in execution, amounts to 0.07 - 0.12 of the length of the interval (7-12%). These figures are found to be in complete agreement with the level of precision of discrimination or reproduction of the corresponding intervals when the intervals are specified by external signals [1, 3].

Thus, it can be assumed that the nervous system (of a mature person) contains a description of a certain set of intervals; the tempo of motion is automatically controlled in conformity with this set and it can be used to measure the length of signal arriving from the outside.

It was further found that the precision with which an organized sequence of actions is performed, a certain interval of the total time of completion (t_0) being reproduced repeatedly, is considerably greater than the precision with which intervals lying within these limits are recognized and reproduced. According to Woodrow, the recognition or reproduction of intervals of 6-30 sec is accompanied by an error of up to 30%; in our experiments, the error is completely an interval of from 6 to 30 sec at various work speeds was 1-5%.

Thus, the execution of an organized sequence of actions sharply defines the reproduction of time intervals. It can be imagined that the measurement of externally prescribed time intervals lying within the limits being considered will be considerably more precise when they are filled with characteristic activity. An examination of the experimental data devoted to this problem will be the subject of discussion in the next publication.

The process of time perception is obviously related to control of the motor activity. This viewpoint is found to be in agreement with the views of Elkin [6] and Smith [5].

We believe that the data presented here contribute to more precise definitions of this viewpoint. These definitions relate to the idea that there exist two functions of control of intervals during which motions are executed, one for maintaining the interval within given limits, the other for changing the interval (Ashby's step function).

The latter, which was up for discussion here, relates to the differences between tempo and rhythm. In accordance with the definition given by Woodrow, we believe that rhythm is a method by which intervals are grouped together.

In preceding investigations [4] we showed that the rhythmic characteristics of executing actions are connected with methods for setting up and storing the order of actions in the memory. The tempo of motions is described either by the number of motions per unit time or by the interval during which an individual motor cycle is completed. In the present article we used the latter description and chose the intervals of motions comprising blocks as such an interval in order not to complicate the description by including the rhythmic characteristics.

Our research has shown that the tempo and rhythm are controlled independently. The rhythm of execution is invariant to a change in tempo, as was demonstrated here.

The temporal organization of a sequence of motions involves separate control of the rhythm and work speed and is related to time description in the nervous system.

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ORGANIZATION OF A SYSTEM OF ACTIONS IN THE CASE OF RANDOM ALTERNATION OF SIGNALS

Ye.S. Rogovenko

In the present investigation we consider one of the new experimental methods of studying the higher nervous activity of man on the basis of the characteristics of a finite automaton with two inputs and four states. The data presented below can be considered as the original data for developing a test which will evaluate man as a decision-making mechanism, relating an incoming signal to the result of a prior action. The importance of working out such tests for the development of space science is without doubt. Since man is a link in a spacecraft and situation control system, it is necessary for him to evaluate control possibilities at any required instant. The present investigation is devoted to this problem.

The classical experiments of I. P. Pavlov's school on animals demonstrated that a dynamic stereotype of conditioned reflexes, developed with regular application of conditioning stimuli, always in the same sequence, can remain invariable if the usual order of sequence of the conditioned signals is interrupted [1, 3, 9]. Relying on these facts, Asratyan [2] expressed the idea that a dynamic stereotype reveals the capability of the brain to program its activity. In our previous experiments with dogs [4] we found that after prolonged application of a stereotype consisting of two alternating stimuli (positive and inhibitive), the formation of another stereotype consisting of new signals, positive only, is complicated by the fact that the reflex to the stimulus that occupied the inhibitive positions of the previous stereotype was reinforced with great difficulty. In Rokotova's experiments [5] with dogs and monkeys it was shown that it is possible to form a system of response reactions that avoids the use of concrete stimuli and is sustained by interreflex links. These facts make it possible to suggest that in the process of forming a stereotype interval links are established between conditioned reactions and that these links are more substantial than those between external signals and response reactions to these signals.

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In the investigations of our laboratory [6, 7], a human being set up lengthy ordered sequences of actions (pressing keys on a panel) in the presence of a conditioning stimulus. In the learning process the test subjects themselves were to establish the order of actions and to reproduce the order correctly. The test subject set up his own program of actions by forming interval links between individual motor acts, in which case the external stimulus fulfilled the role of a triggering signal.

The working out of the dynamic stereotype in the experiment is a particular and, to a certain degree, an artificial example of organization of stereotype activity. It differs from what is done in daily life by the stability of the conditions under which the man or animal has to structure his activity. Let us assume that the man is subjected to a number of actions and does not know in what order they will be applied. Each action in turn may be related to several different reactions, either the one or the other reaction being the correct one, depending on the conditions. In order to realize the correct reactions, the man must evaluate the

conditions under which he must act. It can be imagined that the organization of a system of actions in such a situation proves to be a complicated process, consisting of several problems: classification of all reactions into groups consistent with each of the actions and the establishment of links between reactions within one group and between reactions pertaining to different groups. And to do so it is necessary to consider whether one and the same action is continuing or whether it is changing. If man meets these requirements he will be able to react correctly to any sequence of external actions an unlimited number of times. Naturally, in such a situation the external signals must not lose their value, even when the human being has already formed his system of actions.

A part of the problem of the present research was to determine how man organizes his activity when, in order to make a decision with respect to a consecutive action, he must evaluate the preceding action and at the same time take the prevailing signal into account.

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With this aim in mind we carried out experiments in which the following experimental conditions were set up: 1) a random sequence of two equally probable signals (red and green lights) was used; 2) the actions of the test subjects consisted in pressing four keys arranged in a row in the experimental panel; 3) two possible actions were connected with each signal; and 4) transistions from key to key were established by rules which were pre-set by the experimenter. In bold outline the rules consisted in alternating key-pressing operations related to a specific signal if the signal was repeated several times. If the signals varied, it was necessary to move from one group of keys to another, depending on the location of the preceding action.

The object of this investigation was to study methods of organizing a system of actions and of finding the rules necessary to solve the problem.

METHOD

Test Subjects. These were 9 persons of both sexes, ages 17 to 30, volunteers. The majority had previously participated in psychophysiological tests.

Experimental Setup. This consisted of two panels. The test subjects' panel measured 25 x 35 cm containing four keys, of the inverted N type, arranged in a row, 6 cm apart. Above the keys in the center of the panel were two small lights (red and green), covered with frosted glass. On the experimenter's panel were arranged 4 keys of the inverted N type and 4 small lights wired to the keys of the test subjects' panel. With one of the keys the experimenter triggers a signal on the test subjects' panel. The test subject can extinguish it only by pressing the appropriate key on his panel. At the instant the test subject presses a key, the light on the experimenter's panel that is wired to this key flashes. By means of this set up we were able to monitor the entire course of the search for the correct key.

The instructions were issued prior to starting the experiment and read as follows: "When the red, or the green, signal flashes, you must find the key that will turn it off. If you press a key and the signal does not turn off, continue your search. Your problem is to learn to extinguish the lit signal without error."

Experimental Procedure. The test subject was located in the same room with the experimenter and sat back to back with him during the experiment. The time intervals from the instant the signal was extinguished to the time the next was turned on was 1 to 1.5 sec. The problem was presented to the test subject during a single experiment lasting from 1 to 2 hours. If the test subject asked to take a break, the experiment was recessed for 5-10 min.

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Program. A random sequence of two signals intended for 1000 tests was programmed in a Ural - 2 computer. The probability of appearance of each signal was 0.5. The program of the experiment was put together in consultation with and with the aid of V.I. Varshavskiy. It was based on certain rules characterizing the operation of finite automata. A diagram of the rules is given in Fig. 1. The circles represent the panel keys. Crossovers from key to key on the red signal are indicated by a solid arrow, while those for the green signal are indicated by broken arrows. By the condition of the experiment each signal may trigger two actions. We specified that on the red signal (R) the test subjects had to press either the first or third keys and on the green signal (G) either the second or fourth keys. In view of the random sequence of the signals, the latter could be applied in the following combinations: RR, GG, RG and GR. The operational rules for any combination are as follows: 1) when the signal G is repeated several times in succession, it is required to change alternately from the 2nd to the 4th and from the 4th to the 2nd keys; 2) when the signal R is repeated several times in succession, it is required to change alternately from the 1st to the 3rd and from the 3rd to the 1st keys; 3) if the signal R is followed by the signal G, it is required to change over to the next key on the right; 4) if the signal G is followed by the signal R, it is required to change over to the next key on the left.



Figure 1. Diagram of the Rules of the Experimental Program. The Circles Represent the Keys of the Panel; the Solid Arrows are Changeovers on the Red Signal; the Broken Arrows are the Same for the Green Signal.

The realization of these rules in the experimental program was incident to establishing a series of moves by the arrows of a graph which would be superimposed on the random series of signals. In the experiment the experimenter reproduced the program by simultaneously turning on the signal (from the random series) and "unlocking" a specific key (according to the diagram of the automaton). The problem of the test subject consisted in identifying the signal and searching for the key which at the given instant would extinguish it. The signal could be turned off by the key that

was "opened" by the experimenter and occupied a specific position in the scheme of the automaton.

Indexes. All the correct and erroneous responses of the test subject during the learning period.

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Learning Criterion. The problem was considered to be completed when the test subject followed his last error by three correct repetitions of all the programmed moves in accordance with the arrows of the graph.

Experimental Results

Our experiments demonstrated that all the test subjects learned the proposed problem after 276 ± 53 applications of the signals. It was found that after 20-30 signals all the people, regardless of the individual differences in speed of learning, began to observe certain regularities in the erroneous actions. In the majority of cases the errors were noted in the same combinations of signals and were identical in various test subjects.

Under our experimental conditions, each person was to perform two tasks: divide the entire set of his actions (pressing four keys) into two subsets (pressing two pairs of keys), connect each of them with a distinct signal and establish the transitions from one action to the next when the same signal was repeated and when the signals changed. Therefore, in analyzing the incorrect actions, all the errors were divided into two groups. Referred to errors of the first group were those cases when the test subjects completed actions which were related to another signal. A diminution of these errors should have indicated how people distribute their actions relative to the signals. Referred to errors of the second group were those cases when the test subjects executed an action connected with the prevailing signal, but which was not the right one at that instant. A reduction of errors in this group should have indicated how the people established relations between actions and various signal combinations.

In order to be able to compare the data of individual test subjects we made use of the Vincent-Hilgard method [10]. For each test subject the entire learning process (number of trials required to achieve the learning criterion) was taken as 100% and was divided into five equal periods—20, 40, 60, 80 and 100. In addition, we analyzed the incorrect actions within each learning period. We calculated the relative error frequency of the 1st and 2nd groups as a function of the total number of responses, taken equal to 1. The data are presented in Fig. 2. From the first period we selected the initial learning instant during which the test subjects for the first time found all the programmed crossovers (zero point). Given on the curves are the errors of the 1st and 2nd groups made by the test subjects during the learning process (average values from 9 test subjects).

As is evident from Fig. 2, in the very first learning period (the zero point) the error frequency in both groups was approximately the same, namely, 0.27 and 0.25. Then the errors incident to a lack of knowledge of the relations between actions and signals (1st group) dropped appreciably behind the first half of learning. The relative error frequency at the end of the second period decreased from 0.27 to 0.09. The errors connected with ignorance of the specific transitions between actions (2nd group) decreased during the same period to a considerable degree, i. e., from 0.25 to 0.19. The principal decrease of errors in the 2nd group was observed only at the end of the fourth learning period. The relative frequency of these errors in the third period was 0.16 and in the fourth 0.09.

These data permit us to conclude that in organizing a system of actions under random signal conditions the test subjects first and foremost divided their actions into two groups and related each of the groups to a specific signal. Then they established transitions between definite actions.

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The next question on our research agenda touched on the method of finding rules which could be used to form a system of actions. In the program we used in teaching the test subjects all transitions were encountered with equal frequency and were governed by rules set up for any possible combination of signals. Since the people were able to learn the given program, it could be assumed that they somehow acquired these rules. It is not out of the question that the test subjects set up rules similar to the ones we used. If this is the case, then probably the transitions from key to key, carried out with the same signal combinations, were acquired by the people as some sort of a whole, i.e., as a rule. Then the difference in speed of evaluation between these transitions should be less than the difference between one of these transitions and any other one connected with a different signal combination. In order to throw light on this aspect, we determined the speed with which the test subjects learned to execute all the programmed transitions without making an error. The learning speed was expressed as the number of applications of each transition required for completion of the transition five times without an error (number of trials). The overall data obtained with the 9 test subjects are given in Table 1.

From the table it is evident that when the same signal was repeated the people learned the correct actions faster than when the signals were changed. Since the transitions incident to various signal combinations differed from each other, the difference in speed of evolution of the individual transitions was checked by making the following comparisons: 1) transitions upon "G-G" signal combinations, i.e., transitions between the 2nd and 4th keys; 2) one of these transitions with a transition attendant upon the "R-R" signal combination, i.e., transitions from the 4th to the 2nd key and from the 3rd to the 1st key; 3) transitions carried out in response to the "R-G" signal combination, i.e., transitions from the 1st to the 2nd and from the 3rd to the 4th key; 4) one of these transitions with the transition incident to the "G-R" signal combination, i.e., from the 1st to the 2nd and from the 2nd to the 1st key.

TABLE 1. Speed of Evolution of Various Transitions

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Possible signal combinations	Transitions established by the program	Speed of evolution of transitions (number of trials)
Red - red	from 1st to 3rd key	25
	from 3rd to 1st key	27
Green - green	from 2nd to 4th key	74
	from 4th to 2nd key	62
Red - green	from 1st to 2nd key	104
	from 3rd to 4th key	108
Green - red	from 2nd to 1st key	199
	from 4th to 3rd key	124

The reliability of the differences was tested by the t criterion. The differences were considered to be reliable if $P \leq 0.01$. The data are given in Table 2.

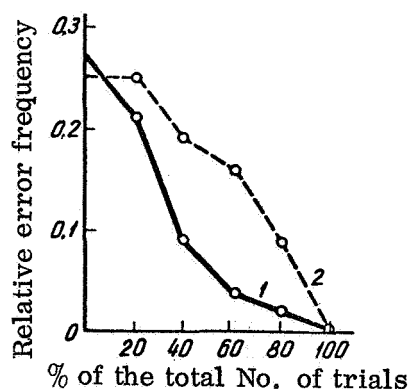


Figure 2. Relative Frequency of Errors in the Learning Process.

1—Errors of the 1st Group;
2—of the 2nd Group.

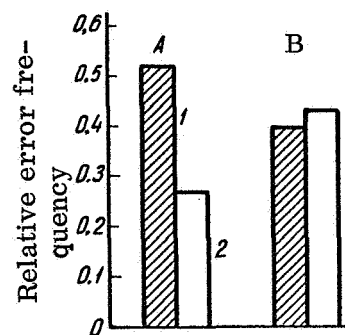


Figure 3. Relative Error Frequency When Repeating the Green (1) and Red (2) Signals.

A and B are the Groups of Test Subjects.

TABLE 2. Differences in Speed of Evolution of Transitions

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Cases compared	Diff. in speed of evolution (no. of trials)	Reliability level	Cases compared	Diff. in speed of evolution (no. trials)	Reliability level
1	12	$0.2 > P > 0.1$	3	76	$0.3 > P > 0.2$
2	35	$0.1 > P > 0.001$	4	95	$0.01 > P > 0.00$

From the table it can be seen that only the differences between transitions relating to different signal combinations were reliable. This means that the people combined transitions in accordance with their common characteristic, a combination of signals, and set up their operational rules for each combination.

Examining the speed of evolution of the individual transitions, we took notice of the fact that on the first repetition of the red signal, seven of the 9 test subjects chose the correct key, while on the first repetition of the green signal, on the contrary, only 2 test subjects did not make a mistake. When we followed the sequence of signal from the very start of our program, it turned out that the red signal was repeated for the first time after the green signal had already been repeated ten times:

R GGGG R GGG R GGG R GGG R GG RR GG R GG RR
GG R GGGG R G R GGG R G R, etc.

Then we compared the number of incorrect responses in the first 10 repetitions of the green and in the first 10 repetitions of the red signals. These data are presented in Fig. 3, A (average data from 9 test subjects). As is evident from the figure, on repetition of the green signal incorrect answers amounted to 0.52,

whereas on repetition of the red signal they were 0.27. It is interesting that in ten repetitions of the green signal 8 of the 9 test subjects chose the correct key. On the basis of these data it can be assumed that as early as these learning periods the test subjects determined to a significant degree the relations between actions and signals and a working rule on repetition of a single signal (green). Having found this rule, they applied it to the case of repetition of the other signal, using another pair of keys. There arises the rather important question as to the capability of man to apply a ready-made rule in another, but analogous situation. In this connection we decided to change somewhat the very start of our program so that the repetitions of the red and green signals alternated, retaining the equal probability and random sequence of signals:

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R G R G RR G R GG R G R GGGG RRR G R G RR G R GG
RRR G R GG R G R GGG RR G R GG RRR G R G
RRRR G R, etc.

With the new program we trained 4 people who had not participated in the basic experiments. The average data obtained from these test subjects are given in Fig. 3, B. As can be seen in the figure, the fraction of errors in repeating both signals in the case of this control group of test subjects was almost the same, namely, 0.40 for the green signal and 0.43 for the red signal.

These data allow us to suppose that in finding transitions between individual actions, the test subjects combined them (the transitions) by means of a common feature, which in this case was a signal combination, and established rules for each such combination. Having set up the working rule for one concrete combination, they transferred it to another combination, but similar to the first.

CONCLUSION

In our experiments test subjects were presented with a complex problem which could be executed only by constantly requiring the test subject to perform several logic operations, such as dividing all the actions into groups related to different signals and setting up rules for transitions from one action to the next within one group and between actions associated with different groups. The aim of the investigation was to discover how people establish rules which must be known in order to solve the given problem.

Analysis of the incorrect actions taken by the test subjects during the learning process demonstrated that it was primarily the errors representative of the degree of knowledge of the relations between the actions of the human being and the external signals that decreased. Errors attendant upon ignorance of the specific transitions between actions were retained almost throughout the learning process and decreased only toward the end. The literature contains data indicating that the relationship between correct and incorrect responses at different periods of the learning process may typify the degree of difficulty of the problem to be solved. Howland [11] presents two types of learning curves. In his opinion, characteristic of easy problems is the abrupt decrease in errors at the beginning of the learning process, and at the end for harder problems. If our data are examined from this viewpoint, it can be surmised that the classification of all actions into

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two groups related to each of the signals was an easier task for the test subjects than the finding of rules for transitions between actions. Hence it can be concluded that in forming a system of actions in the case of random signals, people organize their activity so that they first divide all the actions into groups consistent with the external signals and then attack the problem of setting up rules for transitions between actions. In doing so they must find rules for the cases of repetitions of one signal and for cases of changing signals.

When we determined the speed at which a human being established links between individual actions, we found that transitions made on the repetition of signals were evolved quicker than transitions made on the change of signals. These data permit us to assume that the finding of working rules in the case of continuous action of a single signal is easier for man than when signals changed.

According to the data of our laboratory [8], in working up programs containing a constant order and a constant number of motor acts, people used the mechanisms of grouping elements (individual actions having some sort of common feature are combined into groups which appear as a unified whole) and the mechanisms of successive acquisition of these blocks of actions. It can be assumed that when people perform actions in response to a random sequence of signals, they have also grouped these actions. In our experiments, the features linking actions may have been signal combinations, in response to which actions were executed. An examination of the difference in speed of evolution between transitions relating to different signal combinations permitted us to make this assumption. Then, in case actions performed upon repetition of a single signal are grouped together, an independent system of actions, incident only to multiple repetition of this signal, may be formed. The same is true when a second signal is repeated. Since the signals were transmitted in random sequence, the number of signal repetitions, and therefore the number of actions within each such system, changed continuously. A change in signal terminated the application of one system and transferred the activity of the test subject to the next system. In order to prevent making errors, the test subject would have had to learn, in this case, to change over from any point of this system to any point of the other. But to do this it was not enough to evaluate the present signal and to decide whether the same action was continuing or was changing. In order to establish such transitions, the test subject would have had chiefly to keep in mind the position of his preceding action. According to our data, the establishment of transitions incident to evaluation of a prior action and to allowance for the present signal presented the test subjects with the basic difficulty of organizing a system of actions.

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Despite the fact that the classical concept of a dynamic stereotype includes as a necessary condition the existence of always the same sequence of actions in response to a constant series of signals, we thought it was possible to assume that the form of human activity we studied is not only complex, but also stereotype, because the test subject learned to execute, in a regular fashion, the same combinations of actions each time the conditions under which he had to make a decision coincided. Having acquired all the rules contained in the program, people were able to execute actions an unlimited number of times, each time making the right choice.

The fact that rules formulated for operating in response to repetition of a single signal are transferred to the case when the second signal is repeated

indicates that, on organizing their activity, people may use ready-made rules and thus apply available knowledge.

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ORGANIZING A SYSTEM OF ACTIONS WITH RANDOM ALTERNATION OF SIGNALS, SEARCH AND CHOICE OF ACTIONS

Ye.S. Rogovenko

In our previously described experiments we showed that in forming a system of four actions (pressing keys arranged in a row on a panel) in the case of a random sequence of two equally probable signals, each of which is connected with two specific actions, man applies a method for devising rules for choosing a decision. In the process of learning such a problem all the test subjects (9 persons) first divided their actions into groups corresponding to signals, then established working rules within each group for repetitions of signals, and finally set up rules of transitions between actions relating to different groups when the signals changed. The experiments also showed that people combine transitions in response to the same sequence of signals to form a general working rule for the given signal combination. /97

In learning the problem, each action of the test subject was a repetition of the action of the experimenter, who, by triggering a signal, simultaneously "opened up" the key on the test subject's panel that corresponded to the predetermined program. Thus, a specific program of actions was imposed on the test subjects and they had to learn to reproduce it. In view of these experimental conditions, the test subjects were not able to display all the capabilities available to man in organizing his activity.

It is well known, for example, that people can choose a specific order of actions from several possible ones and can constantly maintain this order. Andreas and Miller [4] presented test subjects with the problem of working through a word maze, which required them to reproduce several times a given phrase, connecting the letters, which were scattered over the page, with a line, always in the same order. As the training improved, the test subjects began to choose a specific route and the probability that the previous route would be repeated at the tenth trial increased to 1.00. There are data testifying to the fact that not infrequently different people choose the same methods of action. In Liberman's experiments [5] the test subjects were asked to predict how three balls would hit three squares under the condition that each ball would hit each square with equal probability. The majority of the test subjects made the same assumptions. Of 27 possible ways the balls might hit, only 2 were predicted with the greatest frequency: either the three balls would hit one square, or each of the three balls would hit each of the three squares.

Thus, man can choose some method of solving a problem, probably the one most suitable for him, and can constantly stick to it. If one and the same problem is presented to a group of test subjects, the majority will make the same choices.

Continuing our research on the study of complex forms of stereotypic human activity, we decided to find out how test subjects would form a system of actions in the case of a random sequence of two signals if they are given the possibility of choosing the next action from several possible ones.

For this purpose the test subjects were asked to solve the same problem as in the preceding experiments, but not with 4, but 12 keys, arranged 4 to a row on the panel. The free choice of one of several possible actions was ensured by connecting the keys of each column (three each) in such a way that the response would be correct regardless which of them the test subject pressed. The test subjects were not told anything about this feature of the panel. /98

In this experiment the human problem was considerably more complicated. In addition to the fact that the test subjects had to organize a system consisting of a larger number of actions (pressing 12 keys), they themselves had to choose specific transitions between actions. On the other hand, the structure of the panel permitted them to reduce the number of actions to four, if they guessed the way the keys were connected.

Thus, the test subjects would have had to reproduce only part of the experimental program in changing over from one column of keys to the next, and they chose the keys and fixed the transitions between them according to their own discretion.

The problem of the given experiment was to study how does man form a system of actions when he is capable of freely choosing specific transitions between individual actions and how, under the conditions of the given experiment, can people reduce the number of their actions.

METHOD

We gave a detailed description of the experimental method in the preceding communication. Here we will dwell only on those details which were added to the method especially for the given investigation.

The Test Subjects were eleven persons of both sexes, ranging in age from 16 to 30, volunteers, not having participated in the experiments of the preceding investigation.

The Experimental Setup consisted of two panels. Twelve keys of the inverted "N" type were arranged four to a row on the test subject's panel. Four keys of the same type were arranged on the experimenter's panel; each of them was connected to three keys on the panel of the test subject (Fig. 1, A). With one of the keys the experimenter turns on a signal on the test subject's panel and simultaneously "opens" the column of keys that is connected to this key. The test subject can extinguish the signal by pressing any of the three keys of the "open" column.

The program was made up according to the same principle as in the preceding experiments. A diagram of the rules by which the given program was set up is shown in Fig. 1, B. The working rules for each possible signal combination were as follows: /99

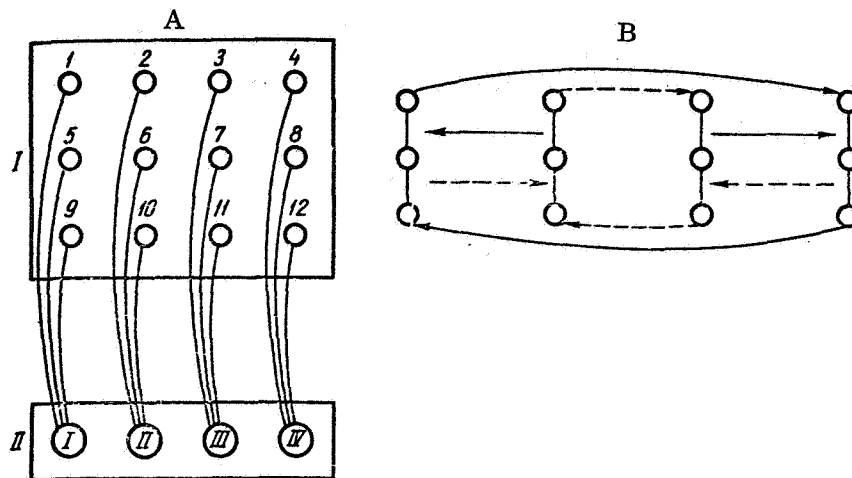


Figure 1. Diagram of the Experimental Arrangement (A) and of the Rules for the Experimental Program (B).

I—Test Subject's Panel; II—Experimenter's Panel. Circles - Keys of the Panel; Solid Arrows - Transitions on the Red Signal; Broken Arrows - Transitions on the Green Signal.

1) when the green signal was repeated several times in succession, it was required to go in turn from one middle group of keys to the keys of the next middle group;

2) when the red signal was repeated several times in succession, it was required to go in turn from one outer group of keys to the keys of the next outer group;

3) when the red signal was followed by a green signal, it was required to go from the outer groups of keys to the keys of the adjacent middle group;

4) when the green signal was followed by a red signal, it was required to go from the middle groups of keys to the keys of the adjacent outer group.

The instruction issued to the test subjects before beginning the experiment, the investigational procedure, the indicators and the learning criteria were the same as in the preceding experiments.

Experimental Results

The experiments demonstrated that all the test subjects were able to organize their actions into a system that corresponded to the experimental program. Since the methodological approach we used permitted a free choice to be made of the specific transitions between keys, it proved possible to combine the results of the test subjects and to consider them as mean data for the group as a whole. An analysis of the data was begun by examining the responses of each test subject. In doing so we singled out two forms of responses — general and exact.

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Among the general responses we classified those cases when the test subjects completed actions incident to the prevailing signal. For example, in response to the red signal they pressed the keys of the outer groups, and on the green signal, the keys of the middle groups. Consequently, the general responses contained both correct actions, when the test subjects chose keys of the group which corresponded to the rules of transitions between actions, as well as incorrect actions, when they chose keys of another group.

An increase in frequency of the general responses should have indicated that the test subjects found rules which governed the relations between groups of actions and each of the signals. Considered to be exact responses were only correct actions. An increase in exact actions was taken to indicate how rapidly the test subjects discovered the rules governing transitions between concrete actions. Comparison of the results of analyzing the response actions made it possible to divide the test subjects into two groups which differed sharply from each other in the way the general and exact responses increased. The data are presented in Figs. 2 and 3. Plotted on the axis of abscissas is the learning level in % of the total number of trials; on the ordinate axis is the relative frequency of responses from the total number of actions of the test subjects, taken to be unity. The curves in the figures show the relations between the general and exact responses for the test subjects of the first group (mean data of seven people) and of the second group (mean data of 4 test subjects). As is evident from Fig. 2, A, the relative frequency of the general responses from the test subjects of the first group was 0.92 already at the end of the second period; at the end of the third period it was close to 1.00. The exact responses of these test subjects increased more slowly, and despite the fact that all the test subjects derived the learning criterion (three-fold correct execution of all the moves stipulated by the program in accordance with the arrows on the graph), the mean frequency of exact responses in the last period was 0.94. Such a relationship between the general and exact responses indicates that the test subjects first divided their actions into sets attendant upon each of the signals, and then established transitions between individual actions. Shown in Fig. 2, B, are both types of responses to repetition of the same signal, and in Fig. 2, C, the same responses, but to a change in signals. When signals were repeated, the principal increase of both the general and exact responses was observed at the start of learning, and in the third period their frequency had already exceeded 0.90, reaching, respectively, 1.00 and 0.99 at the end of the last period. When signals were changed, the exact responses lagged considerably behind the general ones and their frequency at the end of learning was 0.89.

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In essence, the data of the 1st group of test subjects did not differ from the results obtained in our preceding experiments, when they formed a system of four actions.

No difference was observed between the general and exact responses of the 2nd group of test subjects. Regardless of whether we examined the relationship between responses as a whole (Fig. 3, A) or separated the cases of signal repetition (Fig. 3, B) or signal change (Fig. 3, C), both types of responses increased slowly and their relative frequencies at the end of learning were lower than in the test subjects of the first group. The data obtained from the second group of test subjects reveal that they did not divide their actions into sets relative to different signals, but applied another strategy to find rules for the choice of a decision.

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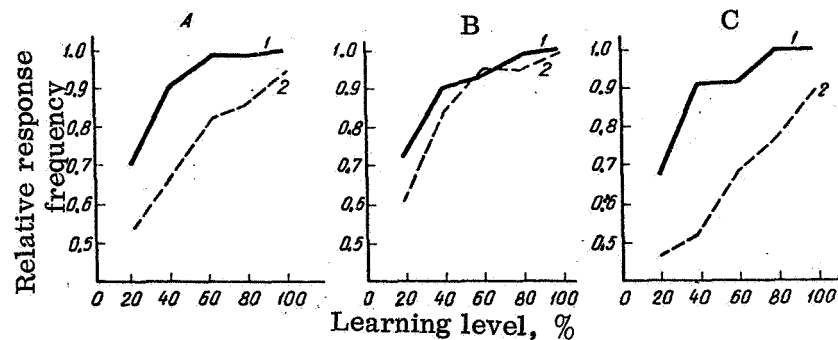


Figure 2. Relations Between the General and Exact Responses for the Test Subjects of the First Group.

A—Of all the Responses as a Whole; B—With Signal Repetitions; C—With Change of Signals. 1—General Responses; 2—Exact Responses.

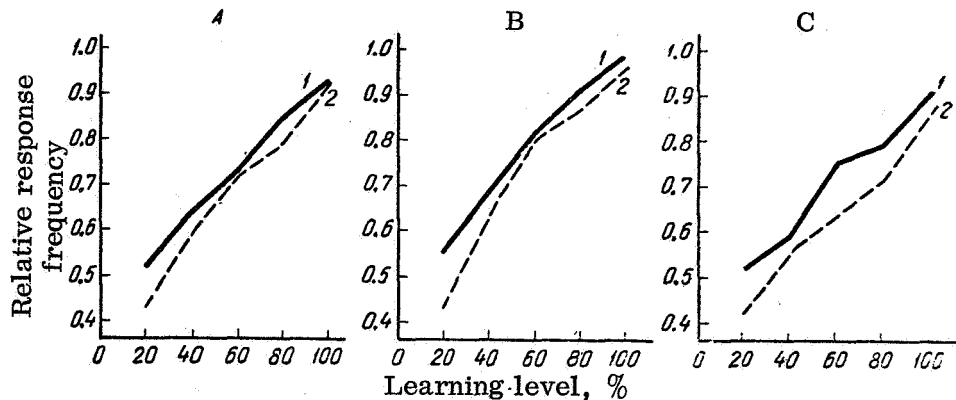


Figure 3. Relations Between General and Exact Responses for the Test Subjects of the Second Group. Notation the Same as in Fig. 2.

At the same time as we analyzed the responses of the test subjects we considered how many keys they use to organize a system of actions. Even in this case substantial differences were found between individual test subjects. The data are presented in Table 1, where the following points were entered for each test subject: 1) number of keys he used at different learning levels (from 5 to 100%); 2) learning speed (number of trials required to discover the learning criterion); and 3) membership in the 1st or 2nd group, depending upon the nature of the growth in general and exact responses. As evident from the table, three people immediately began organizing a system of four actions. Six people began to learn by using 12 (in one case 10) keys and reduced the number of keys to 4 at various learning levels.

In addition we attempted to compare the learning speed with the number of keys used. If we determine the speed at which the test subjects occupying the first five positions in the table learned, that is, those people who used only four keys at the very start of learning, it turns out that one test subject needed 1400 trials to achieve the learning criterion, another only 80. The learning speeds of the other three people were 200, 200 and 355 trials. If these data are compared

TABLE 1. Number of Keys Used By the Test Subjects to Organize a System of Actions

Test subjects	Group	Learning speed (no of trials)	Learning level, in % of the total number of trials																			
			5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
G.M.	1st	200	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
L. Shch.	2nd	355	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
V.R.	1st	200	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
A.N.	2nd	400	12	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
T.F.	1st	80	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
V.Ch.	2nd	700	12	12	12	12	12	12	12	12	12	12	12	12	4	4	4	4	4	4	4	4
V.G.	1st	600	12	12	10	10	10	10	10	10	10	10	10	10	11	10	4	4	4	4	4	4
V.B.	2nd	500	12	12	12	12	12	12	12	12	12	12	12	12	8	8	4	4	4	4	4	4
A.Sh.	2nd	170	12	12	12	12	12	12	12	12	12	12	12	12	12	12	4	4	4	4	4	4
L. T.	1st	245	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
Ya.N.	2nd	1700	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12

with the learning speeds of the test subjects occupying the last two positions in the table, it turns out that one man learned in 245 trials, the other in 1700. Both of them formed a system of 12 actions. These data do not permit us to conclude that the number of keys used has any effect on the learning rate.

The last question we examined was the relationship between the number of keys used and between the general and exact responses. In the given case such a relationship was observed, since all the test subjects who changed to 4 keys at the very initial learning levels belonged to the first group insofar as the relations between general and exact responses are concerned. All the people who belonged to the second group either reduced the number of keys at a considerably later period or continued using all the keys of the panel to the very end of learning.

When we attempted to compare the learning rate of the first and second groups, it was found that there were test subjects in both groups who rapidly organized a system of actions and also slowly (80, 200, 600 and 1400 trials in the first group; 170, 500 and 1700 trials in the second group). Despite this fact, the mean learning rate and the mean error for the first group was 363 ± 199 , and 767 ± 329 /104 trials for the second group. We cannot judge the statistical reliability of these differences in view of the small number of groups, but it can be assumed that the learning rate depends on how the test subjects acquire rules for choosing a decision.

Analysis of the data showed that if the test subjects are given some freedom in choosing actions, they apply different methods of finding rules for the choice of a decision. Therefore it was necessary to examine two aspects: what rules do the test subjects use in organizing a system of actions (do they discover the same rules we used to set up the experimental program, or do they formulate their own rules) and attempt to find out what method of search for rules in choosing a decision the test subjects of the second group applied?

In our first communication we described in detail how, on the basis of differences in rate of evolving individual transitions, it was found that people combined transitions carried out in response to one and the same sequence of actions into a working rule for each possible signal combination.

In the present paper we used this method to determine whether the test subjects discovered the rules of transitions we used as a basis in setting up our experimental program? For this purpose we determined the speed with which transitions between individual sets of keys were involved and compared the differences between transitions combined by a common signal combination (separately for each group of test subjects). The reliability of the differences was verified by the t criterion. The differences were considered to be reliable for $P \leq 0.01$. These calculations did not reveal reliable differences in the rate of evolution between individual transitions for the test subjects of either the first or second groups ($0.2 > P > 0.1$).

Consequently, when people had a free choice of transitions between actions, they did not find working rules for each signal combination, but formed a system of actions by another method.

The analysis we made of the data showed that in the process of learning most test subjects reduced the number of their actions to four. Having the possibility of choosing any of the three keys of each group, the test subjects were able to

establish transitions between actions according to their own discretion, using other rules. Therefore we decided to find out the keys on which test subjects fix their choice. It was found that toward the end of the learning cycle three test subjects began to use the four keys of the upper row, and two chose the keys of the middle row. The other four fixed their choice on keys of different rows. When we examined the paths which they transversed in moving the arm from the keys of one row to those of another row, it was found that the test subjects described, by their motions, so to speak, figures over the surface of the panel. Graphic illustrations of the motions of the arm by a human being are shown in Fig. 4, which contains a schematic representation of the panel and the keys arranged on it. Arm motions executed on the red signal are shown by a solid arrow and on the green signal by a broken arrow. Shown in the figure are the motions of the four test subjects who fixed their choice on four keys located in different rows (I, II, III, IV). As is evident from the figure, in transferring their arms from key to key they described closed symmetrical figures over the surface of the panel. The data of test subject T-a, who organized a system of 12 actions, are shown in Fig. 4, V(a, b, c, d, e, f, g, h). Despite the large number of transitions between various keys, completely symmetrical actions of the test subject were observed in this case also.

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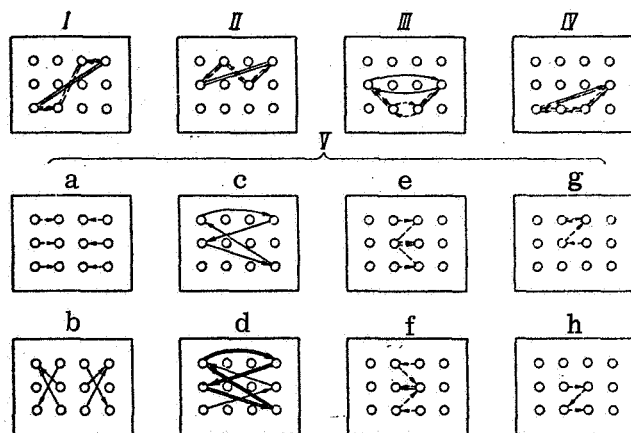


Figure 4. Schematic Illustrations of the Motions of the Human Arm: The Blocks Represent the Panel, the Circles Inverted "N" Type Keys. The Solid Arrows Show the Direction of Arm Motion to the Red Signal and the Broken Arrows, to the Green Signal. I, II, III, IV, V (a, b, c, d, e, f, g, h) are the Motions of the Arms of 5 Test Subjects Over a Two-Dimensional Space.

These data permit us to state that when test subjects have a free choice of keys on the panel, they form a system of actions by creating closed symmetrical figures over the surface of the panel and, in moving from one set of keys to the next, they describe a sort of figure by the motion of their arms.

CONCLUSION

In this investigation our problem was to determine: 1) how man forms a system of actions when he has a free choice of one of three possible actions; and 2) can people in the course of learning reduce the number of actions if the working panel contains an excess

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number of keys.

In the preceding experiments it was demonstrated that when people formulated a system of four actions, during the learning process they discovered the rules by which the experimental program was set up. In the experiments whose results we considered in the present article, the test subjects had to organize a system of

4-12 actions under the condition that the test subjects were presented with a free choice not only of their own actions (choice of any three keys of each set), but also of the transitions between actions (transition from the keys of one group to those of another).

The experiments showed that under the conditions of the given experiment, all the people organized a system of actions. In analyzing the material, however, it was found that one group of test subjects (7 people) was able to only partially find rules for choosing a decision. These people divided the entire set of their actions into two groups and established relations between each group and the pertinent signal. But they were not able to combine the various actions performed in response to the same signal combination and to find transition rules for these actions. After dividing the actions into groups corresponding to signals, these test subjects began to use another strategy to find the correct solution. The second group of test subjects (4 people), from the very start of the learning process, did not divide their actions into blocks in response to each of the signals and formed a system of actions by another method

Since in these experiments the actions of the test subjects could be executed in two-dimensional space and not in a straight line (as was the case when a system of four actions was organized), it was possible to assume that the test subjects found points of focus on the surface of the panel and formed the system of actions as two-dimensional figures. In the investigations of our laboratory [3] it was shown that in forming a sequence of actions a human being combines individual motor acts into blocks, and if in executing a block of actions his hand describes some sort of closed symmetrical figure on the surface of the panel, this block is easier to acquire than blocks of actions which do not form a pattern.

If the test subject found a point belonging to the outline of the pattern, he filled in the rest of the outline by choosing the next points.

When we analyzed how people transferred their arms when moving from key to key and travel sketches of these paths, it turned out that in forming a system of actions in two-dimensional space all the test subjects put together completely symmetrical geometric figures on the surface of the panel.

Hence it can be concluded that the dominant factor in organizing a system of actions in two-dimensional space is how to choose actions which will ensure the construction of a figure in space. Therefore, in our experiments the test subjects did not discover working rules for each possible signal combination, but used a method whereby they found points on the surface of the panel which would allow them to organize a symmetrical figure. Having found such points, they established transitions which gave shape to the figure.

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The second aspect dealt with the capability of people to reduce the number of their actions. During the learning process the majority of test subjects reduced the number of keys they used to four.

The literature contains data testifying that in the execution of motor tasks man tends to reduce the number of motions, retaining only the most essential actions. Arana and Sokolov [1, 2] studied in man the tactile perception of letter imprints or the discovery of checkers in various area elements of the working

space. The authors found that people first felt their way systematically over the entire surface on which the letter or checker was displayed and, as they gained experience, began to check only those spots which might be informative.

Under our experimental conditions, when two successive signals changed positions in a random sequence, it was difficult to find out how people changed over from a large number of actions to a smaller number. Therefore it can be said that a feature inherent in man is the reduction of the volume of actions in organizing a system. The question as to how he reduces the number of actions in solving logical problems connected with the finding of rules for making a choice of decisions deserves special attention and may be the subject of a special investigation.

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COMPARATIVE SPEEDS AND VARIABILITY OF MOTION OF THE FINGERS OF MAN

I. D. Bogina

Among the problems of space biology, one of the most vitally necessary is the problem of evaluating the effector activity of man. On the state of this activity depends the solution of the problem of the relative degree to which an automat or a human being will participate in spaceship control. Of extraordinary importance are the development and substantiation of tests which will permit operative and reliable evaluation, within a short period of time, of human control qualities, such as control of his speed of motion in precise execution of some program of actions.

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However, there are still many unexplained aspects. The first relates to the maximum speed developed by a human being in striking keys with the fingers. The figures cited by various authors fluctuate from 5 - 6 motions per second [5] to 10-11 [2].

The second aspect, which was first examined in detail by Miles, has to do with the possibility that there exists a certain range of fixed speeds of human motions. Miles' data speak in favor of the existence of distinct classes of rates of motion, but must be further clarified, since they contain many cases of overlap.

The third unclarified aspect deals with correlation of the rate of motion between individual fingers of the right and left hands. Goodenough and Tinker [4] emphasize the good correlation in the speed of motion of different fingers of one hand and the poor correlation of fingers of the other hand. Jackson, however, cites contradictory data and says that the speed of motion of the ring and little fingers is slower than that of the other fingers, while Lunderfold [6] cites data testifying that the bioelectric activity of the muscles while typing with the ring and little fingers is distinctly higher than that of the other fingers. Thus, the problem of correlation insofar as speed of motion is concerned remains open.

The aim of the present research reduced to the study of the temporal characteristics of the motion of each finger of the right and left hands, with the test subjects being allowed to freely choose their own speeds ("optimal," "fast" and "slow"). The motions in mind are striking, with the finger, one of the teletype keys intended for the given finger. Each finger struck a key about 100 times in succession at each of the above-mentioned speeds.

The total time spent for each action consisted of the time interval required for accomplishment of the task (the pressing time) and that required to lift the finger and lower it again (the length of the pause).

This kind of experiment permitted us to examine the following aspects of the problem.

1. What are the frequency characteristics of the motion of various fingers of a human being at each of speeds set by himself and what are the relations between the chosen speeds of the different test subjects.

2. How do these characteristics vary and to what extent does the variability depend on the fingers, the speed, and the personal peculiarities.

3. Do any distinct differences exist between the self-set speeds of motion ?

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4. Is the time interval required to carry out the motion organized or random?

METHOD

The motion carried out by the fingers was the striking of keys of an ST-2M teletype machine whose keyboard resembled in form, dimensions, and key arrangement the keyboard of a standard typewriter. Each key of the teletype machine has a contact sensor connected to a multichannel loop oscillograph of the N-102 type. The key notation (letters and numbers) was retained. To the working surface of the fingernail phalanx of each finger of the test subject we attached an electrode (a disk of thin foil, 1 cm in diameter) using BF-6 cement. Thin wires led from each disk and were fixed to the back of the fingers and wrist with leucoplaster; they were connected to the oscillograph by means of removable lasts, different ones for each wrist. Each finger had its own channel.

The records were made on the tape of a multichannel oscillograph at a tape speed of 25 mm/sec.

Contact between the electrode on the finger and the sensor on the key generated a rectangular pulse, the length of which corresponded to the length of contact with the key; the pulse separation corresponded to the finger lifting and lowering time (subsequently referred to as the pause).

The experiment was carried out with 3 test subjects. One of them (V. G.) had completed typewriting school and had experience in typing with all fingers. Two test subjects had typed periodically using the thumb, index and middle fingers of each hand.

The instructions informed the test subjects of the problem, which involved uniform depression of one key with the finger. They were required to work "as fast as possible," were allowed to choose the most convenient "optimal" working speed, and were asked to slowdown the "optimal" rate by a factor of 1.5. The instructions gave the order for change of fingers and working speeds, which were accomplished on a prearranged signal from the experimenter (thus it was not necessary to make an active count of the striking operations).

The same sequence of change of work speed was applied for all the fingers: first the "optimal," then the "fast," and finally the "slow." The experiment began with key-pressing operations by the thumb of the right hand at the "optimal" speed, followed by the same operation with the thumb of the left hand. After both thumbs had run through all the working speeds, they were succeeded by the index fingers in the same order of alternation of speeds and hands, etc.

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The parameters were measured by means of a photoamplifier provided with a measuring grid, accurate to within 10 msec. Measured were all parameters corresponding to length of the pressing actions and to the length of the pauses. The following were computed on the basis of the measurements made:

- 1) the duration of each motor cycle, equal to the sum of the pause length and the pressing time following the pause;
- 2) the mean time of the motor cycle, the mean square deviations and the coefficients of the variations, and the same for the components of the pauses and pressing actions;
- 3) evaluation of the distribution of intervals representative of the duration of the motor cycle.

RESULTS

Given in Tables 1, 2 and 3 are the mean arithmetic data on the lengths of the intervals for execution of motor cycles and their elements, individually for each test subject at various working speeds (fast, optimal and slow performance speeds). Table 1, which gives the corresponding values for test subject V.G. who differs from the others in that she is a professional typist, systematically trained, shows the following characteristics: /111

TABLE 1. Mean Values of the Duration of the Motor Cycle and Its Elements (in msec) for Various Pressing Speeds (Test Subject V.G.)

Finger	Speeds (mean data)											
	Fast				Optimal				Slow			
	No. of measurements	Length of cycle	Pressing time	Transfer time	No. of measurements	Length of cycle	Pressing time	Transfer time	No. of measurements	Length of cycle	Pressing time	Transfer time
Right hand												
1-thumb	—	—	—	—	—	—	—	—	—	—	—	—
2-index	113	220	120	95	123	310	100	215	101	615	375	235
3-middle	108	215	90	130	120	300	95	210	96	615	250	375
4-ring	99	230	100	125	109	380	95	290	107	610	175	435
5-little	69	240	100	140	91	425	110	315	94	610	170	440
Left hand												
1-thumb	—	—	—	—	—	—	—	—	—	—	—	—
2-index	104	245	140	105	124	310	115	200	106	630	330	300
3-middle	106	255	135	120	118	325	100	225	105	610	305	305
4-ring	101	250	165	90	105	405	130	275	102	620	305	315
5-little	88	250	180	75	93	465	180	285	108	595	315	275

- 1) the lengths of the motor-cycle intervals, at each speed, although they differ for different hands and fingers, do not exceed the limits distinguishing the various working speeds;

2) the smallest differences in length of motor cycles between pressing with different fingers and hands at the given speeds are observed for fast and slow work, amounting to 35-40 msec. At the same time, fluctuations in the length of motor cycles between individual fingers in the optimal case reach 165 msec;

3) in comparing the work speeds (at the given tempo) of the individual fingers, it can be seen that in the case of fast speed and, in part, of optimal speed, the fingers of the left hand lag those of the right hand, but at the slow pressing speed this is not observed;

4) fluctuations in key-pressing time for the individual fingers differ from the magnitude of the fluctuations and distribution with respect to the working rates of the entire motor cycle. Thus, at the slow speed, for fluctuations of 35 msec in the duration of the cycles, the magnitude of the fluctuations in pressing time was 200 msec, i. e., almost 6 times greater than fluctuations of the cycle. At the optimal working speed, the magnitude of the fluctuations in pressing time is 85 msec, i. e., one-half the magnitude of the fluctuations of the entire cycle. At the fast pressing speed, the ratio of fluctuation of the pressing time to that of the length of cycle is 2.2, i. e., midway as compared with the ratio of pressing time/length of the cycle at the optimal and slow pressing speeds.

Presented in Table 2 are data on the work of test subject E. F. Let us compare these data with those of the first test subject. From the data of Table 2 it is evident that:

TABLE 2. Mean Values of the Duration of the Motor Cycle and Its Elements (in msec) for Various Pressing Speeds (Test Subject E. F.)

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Finger	Speeds (mean data)											
	Fast				Optimal				Slow			
	No. of measurements	Length of cycle	Pressing time	Transfer time	No. of measurements	Length of cycle	Pressing time	Transfer time	No. of measurements	Length of cycle	Pressing time	Transfer time
Right hand												
1-thumb	120	225	90	165	154	405	155	255	136	575	200	389
2-index	138	255	95	160	91	530	165	365	124	620	185	435
3-middle	164	220	95	130	134	465	130	340	139	720	260	460
4-ring	142	230	115	110	135	475	180	295	117	645	205	435
5-little	128	270	115	140	132	530	215	315	113	695	220	470
Left hand												
1-thumb	74	265	80	185	149	450	150	305	119	625	170	455
2-index	127	245	95	155	109	590	165	420	72	620	170	455
3-middle	136	235	80	160	137	480	145	345	88	760	175	590
4-ring	134	235	100	140	134	500	205	300	115	715	195	520
5-little	122	260	95	165	115	535	225	310	115	735	215	525

1. the values of the motor-cycle intervals fluctuate at the same working speed, but are considerably closer to each other than the intervals characterizing the other speeds. There is only one case of overlap, when the index finger of the

left hand works somewhat slower at the optimal speed than the thumb of the right hand at the slow speed. In all other cases the working speeds differ clearly from each other in magnitude of the motor-cycle intervals.

2. The smallest differences in length of the motor cycles of different fingers are observed at the fast pressing speed, amounting to 50 msec; the optimal and slow pressing rates yield fluctuations of 185 msec between individual fingers.

3. In estimating the distribution of working speed over hands and fingers it can be seen that at the fast pressing speed the left hand does not differ from the right one, but the little fingers lag the others. At the optimal and slow pressing speeds the left hand lags the right somewhat, but the little fingers do not stand out from the rest.

4. Fluctuations in pressing time differ from fluctuations in duration of the motor cycles, but not so sharply as in the case of the first test subject. At the fast pressing speed the magnitude of these fluctuations is approximately equal to the magnitude of the fluctuations of the entire cycle, and at the optimal and slow pressing speeds they are 1/2 the magnitude of the fluctuations of the entire cycle.

Given in Table 3 are data representative of the work of test subject I. B. Comparison of the data of this table with the values considered above reveals the following:

1. the duration of the motor cycles fluctuates for the various fingers at the same pressing speed. But the values of these parameters do not exceed the limits of the given speed in any case;

2. the least fluctuations in duration of the motor cycles of individual fingers are observed at the fast pressing speed, amounting to 35 msec, while the greatest fluctuations (375 msec) are observed at the slow pressing speed. At the optimal pressing speed the fluctuations in duration of the motor cycles for individual figures are 235 msec;

3. the relative pressing speeds for fingers of the right and left hands are the same at the fast speed. At the optimal speed the left hand lags the right somewhat, just as at the slow pressing speed;

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4. fluctuations in the average key-pressing time for the various fingers differ from fluctuations of the entire cycle at the different working speeds. Thus, at the fast pressing rate, fluctuations in the pressing time are 60 msec, i. e., almost double the fluctuations of the entire cycle; at the optimal pressing speed they are also 60 msec, which amounts to 1/4 the fluctuations of the entire cycle, whereas at the slow speed they reach 220 msec, i. e., 0.6 the fluctuations of the entire cycle.

The data given in Tables 1, 2, 3, in addition to the already presented individual differences, also reveal some signs of similarity in the work of all the test subjects. Common for all three test subjects are the following:

1. a distinct difference between the three working rates, evident in the functioning of each of the 10 fingers;

TABLE 3. Mean Values of the Duration of the Motor Cycle and Its Elements (in msec) for Various Pressing Speeds (Test Subject I. B.)

Finger	Speeds (mean data)											
	Fast				Optimal				Slow			
	No. of mea- surements	Length of cycle	Pressing time	Transfer time	No. of mea- surements	Length of cycle	Pressing time	Transfer time	No. of mea- surements	Length of cycle	Pressing time	Transfer time
Right hand												
1-thumb	124	190	90	100	127	325	115	210	103	710	150	560
2-index	147	195	75	120	114	425	90	340	104	700	110	585
3-middle	150	190	80	110	139	260	105	155	139	845	110	745
4-ring	155	180	115	65	126	425	140	285	105	715	135	580
5-little	119	200	135	65	143	400	125	280	112	835	140	695
Left hand												
1-thumb	117	200	110	90	150	350	130	225	100	745	175	570
2-index	145	195	90	105	130	445	95	355	123	895	120	775
3-middle	129	195	90	110	149	285	80	205	103	955	120	835
4-ring	125	210	115	65	128	445	125	320	70	830	125	705
5-little	103	175	115	60	133	400	150	255	61	1075	330	755

2. the smallest fluctuations in duration of the cycles for the various fingers at the fast working rate are 40-50 msec; /114

3. the absolute values of the duration of the motor cycles for each of the given working speeds are close. They fluctuate for the different test subjects from 180 to 270 msec at the fast working speed (4-5 keys/sec), from 285 to 590 msec at the optimal rate (3.5-1.8) keys/sec) and from 575 to 1075 msec at the slow rate (1.8-1 key sec);

These figures characterize the extreme limits of the mean values of the cycles at the given working speed, obtained from at least one test subject and for one finger.

4. the fluctuations of the mean duration of cycles with the various fingers are independent of the fluctuations of a single element of the cycle (the key-pressing operation and the pause).

In analyzing the key-pressing motions it was demonstrated that the motor cycle is a better organized (with respect to time) interval than the components of its elements [1]. The same question arises when evaluating finger motions. An estimate of the independence of the cycle elements is attendant upon the following considerations. If the pressing time and the preparatory time for this action (the pause) were separate independent parameters, the sum of their square deviations would equal the mean square deviation of the entire motion of which they are a part. The appropriate calculations are shown in Table 4. From the table it is evident that the mean square deviations of the entire motion at all working speeds were considerably smaller than the sum of the mean square deviations of the pressing and finger transfer actions. Consequently, the duration of the

TABLE 4. Mean Square Deviations (in msec) of the Time of a Motor Cycle and Sum of the Mean Square Deviations of the Elements Making up the Motion (key-pressing and finger-displacement actions)

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Finger	Test subjects					
	V. G.		E. F.		I. B.	
	σ (motor cycle)	Sum σ of the key-pressing and finger transfer act.	σ (motor cycle)	Sum σ of the key-pressing and finger transfer act.	σ (motor cycle)	Sum σ of the key-pressing and finger transfer act.
Fast speed						
Right hand						
1-thumb	—	—	11,5	17,5	10,0	14,4
2-index	22,5	44,6	14,4	17,4	10,0	38,9
3-middle	13,2	29,9	12,4	27,3	14,1	25,9
4-ring	16,9	43,4	14,2	37,6	21,0	73,5
5-little	18,5	52,9	14,5	50,0	13,5	49,6
Left hand						
1-thumb	—	—	15,3	26,9	13,4	32,4
2-index	22,5	63,4	13,2	16,8	17,6	30,7
3-middle	26,6	57,6	15,8	28,7	20,3	48,3
4-ring	29,5	54,8	15,9	32,6	88,0	93,0
5-little	30,1	73,7	17,8	43,0	44,9	74,2
Optimal speed						
Right hand						
1-thumb	—	—	25,6	40,2	24,1	54,7
2-index	13,7	23,8	26,3	45,0	23,6	47,2
3-middle	14,0	24,6	18,0	47,6	38,9	55,0
4-ring	31,8	48,0	19,0	34,8	22,5	70,0
5-little	39,1	67,5	36,9	54,7	28,0	42,5
Left hand						
1-thumb	39,4	91,7	24,3	40,2	16,3	31,8
2-index	18,5	37,8	26,2	43,9	29,1	75,6
3-middle	23,3	27,4	22,6	50,0	19,8	40,6
4-ring	29,5	58,8	26,9	46,3	28,3	79,8
5-little	33,6	76,2	25,3	49,5	33,2	80,1
Slow speed						
Right hand						
1-thumb	—	—	38,5	55,2	29,2	53,6
2-index	57,4	141,0	30,9	67,5	102,8	125,0
3-middle	42,9	148,0	57,5	103,0	97,1	105,0
4-ring	48,8	92,8	30,9	55,7	95,3	173,0
5-little	51,2	134,5	38,3	62,0	128,6	144,0
Left hand						
1-thumb	—	—	22,1	47,3	29,6	44,0
2-index	53,7	118,0	28,8	62,8	61,5	100,0
3-middle	51,4	136,0	31,1	60,7	47,9	87,0
4-ring	43,8	134,0	40,6	68,0	83,6	107,6
5-little	41,0	159,0	32,2	60,9	195,4	339,0

Note: Commas represent decimal points.

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action and the duration of finger transfer are not independent quantities and we have a right to estimate, as the unit time of motion, the time from the instant the finger is lifted, after completing one pressing action, to the end of the next pressing action, i. e., the duration of the motor cycle.

The time characteristics we obtained for finger motions at the fastest working speed, devoted as the "fast" mode, permit us to state with confidence that there exists a specific mode which is common to all our test subjects. The time characteristics of motion in the fast mode are presented in Table 5.

TABLE 5. Time Characteristics of Finger Motions At the Fast Pressing Rate

Finger	Test Subjects											
	V. G.				E. F.				I. B.			
	No. of measurements	Mean value of cycle (msec)	σ	Coefficient of variation (%)	No. of measurements	Mean value of cycle (msec)	σ	Coefficient of variation (%)	No. of measurements	Mean value of cycle (msec)	σ	Coefficient of variation (%)
Right hand												
1-thumb	—	—	—	—	120	255	11,5	4,5	124	190	10,0	5,2
2-index	113	220	22,5	10,2	138	255	14,4	5,6	147	195	10,0	5,0
3-middle	108	215	13,2	6,2	164	220	12,4	5,6	150	190	14,1	7,5
4-ring	100	230	16,8	7,3	142	230	14,2	6,2	183	155	21,0	11,5
5-little	69	240	18,5	7,7	128	270	14,5	5,4	120	200	13,5	6,8
Left hand												
1-thumb	—	—	—	—	74	265	15,3	5,8	117	200	13,4	6,7
2-index	104	245	22,5	9,2	127	245	13,2	5,4	145	195	17,6	9,0
3-middle	106	255	26,6	10,4	136	235	15,8	6,7	129	195	20,3	10,5
4-ring	101	250	29,5	11,8	134	235	15,9	6,7	125	210	88,1	42,4
5-little	88	250	30,1	12,3	122	260	17,8	6,8	103	175	44,8	25,8

Note: Commas represent decimal points.

The greatest differences between the time of execution of motions by the fingers of one hand did not exceed 50 msec for any of the test subjects. For example, the key-striking time for the middle finger of the right hand of test subject E. F. was, on the average, 220 msec, while the time for the little finger of the same hand was 270 msec. But these differences could even be smaller; for instance, the thumb, index, and middle fingers of the right hand of test subject I. B. were characterized by the same value (190 msec), while the ring and little fingers differed by 20 msec. The times of motion of the fingers of the left hand of test subject V. G. were completely identical.

In two test subjects we observed almost complete agreement in time of motion of the same fingers of the two hands; the differences did not exceed the limits of one σ . In the third test subject these differences reached 2σ in only one case. /117

The fast rates chosen by the different test subjects also were in good agreement with each other. The rates of two test subjects hardly differed and their mean values were 240-250 msec. The third test subject worked somewhat faster, at an average speed of motion of 190 msec. The fastest key-striking speed

reached by our test subjects was 4-5 keys/sec. These values are in complete agreement with the data of Fenn [3], who considers the natural period of the index finger to be 4 cycles per sec, and differ but little from Jackson's results [5], whose test subjects pressed at a speed of 5-6 keys/sec.

The mean key-striking time in our experiment was typical of motions completed in 30-40 sec. In Jackson's experiment the values for the average speed of motion were obtained from the number of strokes made in 10 sec. However, this does not explain the somewhat slower speeds of our test subjects since the pressing speeds remained constant over the entire key-pressing time.

The mean durations of the motions at the fast working rate were characterized not only by the very similar working speeds of the various fingers and test subjects, but also by the relatively small amount of variation characterizing each finger. Very high fluctuations were observed only in the work of the ring and little fingers of the left hand of test subject I. B., who had experience in typing with the thumb, index and middle fingers. The coefficients of variation representative of the work of the other fingers were 5-11%.

The time characteristics of the motions of fingers at the optimal rate are presented in Table 6. This rate was chosen by each test subject as the most comfortable.

In comparing the characteristics of the duration of the motions, it is evident that the difference between the speeds of motion of the various fingers of one hand was 125-160 msec for each test subject. In test subject V. G. it was possible to single out three motions of the fingers of each hand that were almost identical in time, but only two for the other test subjects.

TABLE 6. Time Characteristics of Finger Motions at the Optimal Pressing Rate

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Finger	Test subjects											
	V. G.				E. F.				I. B.			
	No. of measurements	Average length of cycle (msec)	Coefficient of variation (%)	No. of measurements	Average length of cycle (msec)	Coefficient of variation (%)	No. of measurements	Average length of cycle (msec)	Coefficient of variation (%)	No. of measurements	Average length of cycle (msec)	Coefficient of variation (%)
Right hand												
1-thumb	—	—	—	154	405	25,6	6,3	127	325	24,1	7,5	
2-index	123	310	13,7	4,4	91	530	26,3	4,9	114	425	23,6	5,5
3-middle	120	300	14,9	5,0	134	465	18,0	3,8	139	260	38,9	15,0
4-ring	109	380	31,9	8,4	135	475	19,0	4,0	126	425	22,5	5,3
5-little	91	425	39,1	9,2	132	530	38,9	6,9	143	400	28,0	7,0
Left hand												
1-thumb	—	—	—	—	149	450	24,4	5,4	150	350	16,3	4,7
2-index	124	310	18,5	6,0	109	590	26,2	4,5	130	445	29,1	6,5
3-middle	118	325	23,3	7,2	137	480	22,6	4,7	149	285	19,8	7,0
4-ring	105	405	29,5	7,3	134	500	26,9	5,4	127	445	28,3	6,4
5-little	93	495	33,6	7,2	115	535	25,3	4,7	133	400	36,2	9,0

Note: Commas represent decimal points.

The agreement between the rates of motion of the same fingers of both hands was fairly well maintained at this working speed also. The differences between the mean speeds of motion of the same fingers were considerably less than the difference between the fingers of the same hand, and only in one case did they reach 60 msec. In all the pairs we compared there was a slight (15-30 msec) predominance in the working speed of the fingers of the right hand. The average pressing speeds of test subjects V.G. and I.B. were 300-450 msec, and of test subject E.F. this was 450-600 msec.

At this rate the amount of variation in the work of each finger was slight. The coefficients of variation were within the range of 4-9%. Considerable fluctuations were observed only in the work of the middle finger of the right hand of test subject I.B.; the pressing speed of this finger was considerably greater than that of the other fingers in working at this rate. The coefficient of variation of this finger was 15%.

Time characteristics of finger motion at the slow rate. The test subjects were obliged to work at a speed lower by a factor of 1.5 than at the optimal rate. The characteristics of the pressing speeds are given in Table 7. In pressing keys at the fast and optimum rates we observed working characteristics which were common to all the test subjects. The pressing speeds at the slow working rate required a separate description for each test subject.

TABLE 7. Time Characteristics of Finger Motion at the Slow Pressing Rate

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Finger	Test subjects											
	V. G.				E. F.				I. B.			
	No. of mea- surements	Average length of cycle (msec)	σ	Coefficient of variation (%)	No. of mea- surements	Average length of cycle (msec)	σ	Coefficient of variation (%)	No. of mea- surements	Average length of cycle (msec)	σ	Coefficient of variation (%)
1-thumb	—	—	—	—	136	575	38,5	6,7	103	710	29,2	4,1
2-index	100	615	57,4	9,3	124	620	30,9	5,0	104	700	102,8	14,8
3-middle	96	615	42,9	7,0	139	720	57,5	8,2	139	845	97,0	11,5
4-ring	107	610	48,8	8,0	117	645	30,9	4,8	105	715	95,3	13,3
5-little	94	610	51,2	8,4	113	695	38,3	5,5	112	835	128,6	15,4
Right hand												
1-thumb	—	—	—	—	119	625	22,1	3,5	100	744	29,6	4,0
2-index	106	630	53,7	8,5	72	620	28,8	4,6	123	895	61,5	6,9
3-middle	105	610	51,4	8,4	88	760	31,1	4,1	108	955	47,9	5,0
4-ring	102	620	43,8	7,0	115	715	40,6	5,7	70	830	83,6	10,0
5-little	108	595	41,0	6,8	115	735	32,2	4,4	61	1075	195,4	18,2
Left hand												

Note: Commas represent decimal points.

Complete agreement with respect to time of pressing of all fingers was observed in the case of test subject V.G., and, therefore, of course, there was agreement between the characteristics of the same fingers. The speed she chose was 610-620 msec per cycle; in the mean, the ratio of this speed to the speeds of the optimal rate was 1.65:1.

The differences in speed of motion between the fingers of each hand reached 140 msec in the case of test subject E. F. We were able to single out two fingers of each hand which pressed at similar speeds. The pressing speeds of the index fingers agreed completely; there were differences between the remaining identical fingers, approximately equal to one σ . The mean ratios of the values of the slow rate to those of the optimum were 1.35:1 for each test subject.

The differences between pressing speeds for the fingers of the right hand of test subject I. B. were 145 msec, while the differences between the thumb and little finger of the left hand were 330 msec and the duration of the cycles fluctuated in the range 745-1075 msec. There was relative agreement between the thumb characteristics. In the work of the other identical fingers there was no agreement, and the fingers of the left hand worked considerably slower than the same fingers of the right hand.

The amount of variation in the work of each finger was also different for each test subject. The coefficients of variation of test subject V. G. fluctuated in the range 8-10%; those of test subject E. F. were very small, remaining within 3.5-8% at this tempo also. The coefficients of I. B. fluctuated from 4-18%. The mean length of the cycle over the entire run of pressing actions by the index and ring fingers of both hands and by the middle and little fingers of the right hand of test subject I. B. and also of the middle finger of the right hand of E. F. was not constant; rather, we were able to observe two average values of the cycle. During the first 30-70 motions the test subjects worked at a faster speed. For example, the average length of the cycle of motion of the little finger of I. B. was 835 msec with a coefficient of variation of 15.4%. However, the first 60 key-striking actions were executed at a speed of 725 msec with a coefficient of variation of 8.5%, and the next 50 motions at a speed of 945 msec with a coefficient of variation of 7.3%.

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The degree of variability of the work of the various test subjects agreed to some extent with the relative duration of the elements of the motor cycle. Shown in Table 8 are the ratios of the length of the pressing actions to the total length of the cycle at each working rate.

The relations between the length of the pressing action and the length of the entire motion, equal to approximately 0.3-0.4, remained constant for test subject E. F. at all the working rates. Consequently, variations in the working rate of E. F. stem from uniform acceleration or deceleration of both the length of the pressing action and the time of finger displacement. At the same time, this test subject was observed to have the most constant working speeds for each finger and the smallest coefficients of variation.

A distinct reduction in the relative pressing time at the slow speed is observed in the case of test subject I. B., whose coefficients of variation were very high. The average values for the pressing time at the optimal and fast speeds were the same and increased only slightly at the slow rate, whereas the total time of the cycle rose by a factor of 2-3, i.e., the working speeds always changed as a result of a change in the finger-transfer time.

There was a clear decrease in the relative pressing time at the optimal rate in the case of test subject V. G.; it amounted to 0.3 of the length of the cycle,

TABLE 8. Relative Length of the Key-Pressing by the Various Fingers at the Different Working Speeds

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Finger	Test subjects					
	V. G.		E. F.		I. B.	
	right hand	left hand	right hand	left hand	right hand	left hand
Fast speed						
1-thumb	—	—	0,38	0,33	0,47	0,55
2-index	0,55	0,57	0,38	0,39	0,38	0,47
3-middle	0,42	0,53	0,30	0,28	0,42	0,45
4-ring	0,43	0,66	0,29	0,26	0,62	0,55
5-little	0,42	0,72	0,25	0,21	0,64	0,62
Optimal speed						
1-thumb	—	—	0,36	0,31	0,35	0,37
2-index	0,32	0,37	0,38	0,39	0,21	0,21
3-middle	0,32	0,31	0,42	0,33	0,40	0,28
4-ring	0,25	0,32	0,50	0,42	0,33	0,28
5-little	0,26	0,39	0,43	0,37	0,31	0,37
Slow speed						
1-thumb	—	—	0,35	0,27	0,21	0,23
2-index	0,61	0,52	0,30	0,27	0,16	0,14
3-middle	0,41	0,50	0,41	0,23	0,13	0,12
4-ring	0,28	0,49	0,32	0,27	0,19	0,15
5-little	0,28	0,53	0,32	0,29	0,17	0,33

Note: Commas represent decimal points.

whereas at the fast rate this relation was 0.4 to 0.7 and at the slow rate 0.3 to 0.6, i.e., the change in speeds occurred as a result of changes in the speed of finger displacement as well as of a change in the key-striking time.

Obviously, the more stable speed is attendant upon the capability of maintaining constant relations between the elements of the cycle.

The degree of variation in the intervals during which the motor cycles were completed is of interest not only from the standpoints already considered, but also insofar as the aspect of methods of controlling the speed of motion is concerned. In the work of Rokotová [1] it was shown that the uniformity of hand motion (key pressing motion) in solving a specific motor task is based on a central interval-generating mechanism for the execution of the motor cycle. By analyzing histograms of the distribution of motor-cycle intervals good agreement was found with the model proposed by McGill, which describes the operation of a rhythmic mechanism specifying intervals and working under noise conditions. These data were obtained for the case of a complex motor problem and the use of the entire wrist as the effector mechanism. In carrying out the present work, we checked the suggestion that the interval-generating mechanism is most clearly manifest when such a simple motor problem is completed as repeatedly striking the same key and when using such a simple motor act as the participation of one finger of one hand in simple coordination activities.

In order to solve this problem we compiled histograms of the distribution of time intervals during which individual motor acts (motor cycles) were carried

out for all the above-described cases. Presented in Fig. 1 is the distribution of the duration of motor cycles of test subject E. F. for the work of the middle finger of both hands at the three working speeds. /122

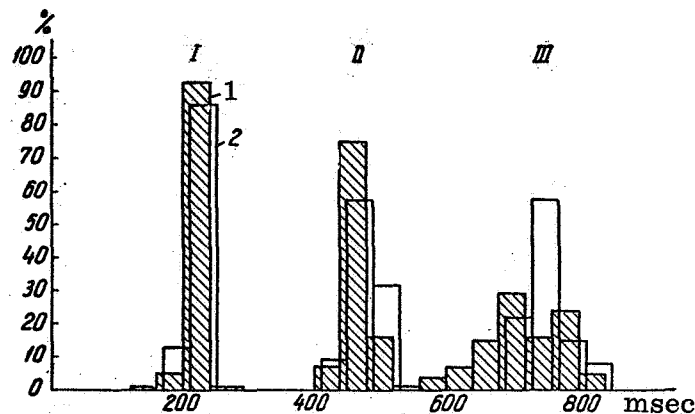


Figure 1. Distribution of the Duration of Motor Cycles for the Middle Finger of Both Hands of Test Subject E. F.:

1, 2—For the Right and Left Hands at the Fast (I), Optimal (II) and Slow (III) Working Speeds.

Deserving of attention is the varying nature of the distribution at the different working speeds of the same fingers and the completely similar nature of the time distribution of finger motion of the hands at the same working speed. The histogram for the fast key-pressing rate consists of one interval in which 85-95% of all cases fall, i. e., almost the entire spread of values for the intervals amounts to 40 msec. Moreover, the value of the peak of the distribution histogram (200-240 msec for the right finger and 210-250 msec for the left) completely describes the time of a motor cycle at the fast pressing speed. The distribution of motor-cycle values at the optimal pressing speed has a somewhat more diffused nature, although it does not change in its essential features (in particular for the right finger). Let us consider the histogram of the right finger. The peak distribution interval (460-500 msec) is very sharply pronounced and takes in 73% of all intervals; the intervals close to the peak one take in 8 and 13% of the intervals and together with the peak interval completely describe the distribution of these values.

The histogram representative of finger operation at the slow speed has essentially a different character. The first thing that strikes our attention is the presence of two peaks for the distribution of cycles of the right finger, which reflects the fact described above, relating to the change in value of the motor cycle at the slow working speed during one and the same execution of this cycle. Furthermore, the histogram reveals the absence of a sharp peak. The values of the intervals are distributed in the range 560-850 msec. Even a rapid survey of the histogram shows that here we are dealing with a process different from the ones governing the fast and optimal speeds. The process is of a more random or, perhaps, inhomogeneous character.

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Let us proceed to evaluate the histograms in connection with evaluating the process on which uniformity of execution of the motor cycles is based. The calculations made by N. A. Rokotova [1] on approximation of the data to the normal distribution and to the distribution of the Laplace function (compound function consisting of regular and random components) led to specific values for the parameters, making it possible to relate the experimental data to one or the other of the distributions. It turned out that the primary parameters were the peak distribution intervals and the intervals closest to them (for the case when the size of the interval is tied in with the value of the mean square deviation and to that of the arithmetic mean).

It was found that the following relative frequencies of occurrence correspond approximately to the normal distribution: 36% for the peak interval, about 24% for the intervals closest to the peak interval; 50-60% of the values in the peak interval will correspond to the Laplace distribution and 15-20% in the adjacent intervals. The peak interval of the optimal speed covers 76% of all values for the right finger and 53% for the left finger. If the histograms are evaluated on the basis of the magnitude of the interval that corresponds to the mean square deviation, the peak of the distribution for the right finger turns out to fall within the interval of 451-470 msec and takes in 53% of all values; the adjacent intervals of 431-450 msec and 471-490 msec cover 18 and 15% of the values, respectively. In the given case, therefore, we are dealing with a distribution of values which are not random, but which reflect the presence of a regular (given) component, in conformity with McGill's model. In order to evaluate the distribution at the fast rate of work let us draw on the values for the relative frequency of occurrence to present the histogram with the magnitude of each interval that corresponds to the mean square deviation (12.5 msec for the right finger and 15 msec for the left). It turns out that 54% of all values is covered by the peak interval, which is, of course, less than the ratios given in the figure, but is considerably closer to the distribution of the Laplace function than to the distribution of the normal (random) function.

Insofar as the distribution of values at the slow speed is concerned, we did not succeed in establishing such clear relations that we could consider the distribution of these intervals as specified.

Thus, from the data we obtained on simple striking of one key by a single finger we can derive information on methods by which the time characteristics of motion are controlled. We believe that these data provide a number of proofs in favor of the viewpoint expressed by Spivack and Levine [8] and others that the time intervals for execution of motions are specified by mechanisms of the human central nervous system. Among these proofs we consider the following:

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1. the great similarity in value of the intervals for all fingers at each given working speed testifies to the possibility that the process is based on a single fixed prescribed interval;
2. the distinct differences between the average values of the intervals at the various working speeds indicates that the working speed is tied in with some interval that is fixed for the given speed;
3. the extraordinary uniformity of the motor-cycle intervals, especially at the fast key-pressing rate;

4. the character of the distribution of the fast and optimal pressing rates, as represented in the histograms.

The experimentally obtained data testify to the high reliability of the experimental approach we used and may serve as a basis for evolving a test which will evaluate the work efficiency of a human operator.

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EFFECTOR ACTIVITY OF A HUMAN BEING IN FIXING PERFORMANCE TIME

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with Assistance from Z. P. Pavlova

Among the tests for evaluating the functional capabilities of a human being on board a spacecraft an important role belongs to tests connected with monitoring operations. Good control of a spacecraft and the situation is possible only on the basis of a continuous and precise evaluation of information on changes in the medium and in one's own activities. Hence, the value of research into the capabilities of man as a servosystem is clear. Given in the present paper are data on the operation of a human being under given time conditions. As will be shown, under such conditions man operates as a system which accomplishes a two-dimensional monitoring operation: of the given time and of the speed of his own actions. The methods applied in this research can be used as tests to evaluate the efficiency of a human operator as a servosystem. /125

The speed of motion is one of the essential variables of the effector activity of a human being: Speed is one of the components which determines the efficiency of execution, and therefore analysis of the mechanisms that regulate speed is important for an evaluation of human activity. There is another aspect which is in need of special consideration. This is an aspect incident to representation of time by a human being and to human activity to be accomplished within fixed time intervals.

Speed of motion (tempo) is a variable which involves the time and number of motions or individual motor acts. It can be defined both in terms of the numbers of motions within a certain unit of time as well as in terms of the time spent in accomplishing a certain fixed number of motions. A convenient representation of speed is the time interval within which a motor cycle is accomplished, since the interval will decrease as the speed increases. Such a representation is convenient because, on the one hand, it yields a criterion for the speed of motion and, on the other hand, it introduces the problem of time estimation into the scope of examination.

At the present time there are two opposing viewpoints as to the mechanism by which time is perceived and estimated. A number of investigators believe that estimation of time intervals is tied in with the perception of external signals [1, 10]. Another group of investigators suggest that time estimation is based on an interval process of generating intergals [11, 14]. In connection with the latter viewpoint, of great importance is the study of the natural effector activity of man within the estimated interval. The possibility of representing the human speed of motion in terms of time intervals paves the way for the assumption that speed of motion participates in time estimation.

All that has been said clarifies the meaning of the research into the effector activity of man within fixed time intervals as presented in the present article.

The subject matter of the experiments consisted in the repeated execution by test subjects, within a time interval fixed by the experimenter, of a thoroughly learned sequence of actions (pressing keys on a panel in a strict order) consisting of 24 individual motor acts. The questions which may be answered by such an experiment can be formulated as follows.

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1. Inasmuch as the work to be done by the test subject is attendant upon a fixed overall completion time, he will have to keep track of the prescribed interval. How accurately can he do this?

2. Since the time of completion of a single motor cycle is not prescribed, we are not sure whether it is random or is fixed by the test subject himself.

3. If errors are made in keeping track of the interval, the question is what are their qualitative characteristics so as to determine the probability of estimating and compensating for them.

4. What is the character of compensation of errors committed in keeping track of the interval and is this character connected in some way with the speed of motions (the length of the interval during which a motor cycle is completed)?

METHOD

A detailed description of the experimental arrangement, of the principles on which the motor problems were based and methods of analyzing the results has been given in the preceding publications [4, 5, 6, 7].

The main portion of the present paper is devoted to studying the accomplishment of a series of actions with the time specified. In complementary experiments a study was made of the execution of a series in a given time, with the test subjects themselves estimating the errors, and of the distinction made by the test subjects in the prescribed intervals.

In the main series of experiments 15 test subjects of both sexes, volunteers, aged 18-45, with high-school or college education, participated.

The problem consisted of 24 sequential depressions of 8 keys on a panel. The order of actions was organized spatially taking into account the predetermined facts of grouping of individual actions. The order proposed in this study allowed for the possibility of organizing blocks of 3 or 6 actions. If the keys of the panel are numbered

1234
5678, the problem can be written as
1 5 6 4 8 7 3 2 7 2 3 6 8 3 4 5 2 1 7 6 1 6 7 4.

Experimental procedure. The test subject was informed of the key numbering system and received a sheet of paper on which the problem was written down numerically. Within 20-30 min the test subject learned by himself, from the paper, to reproduce the prescribed order of the actions from memory. After the

problem had been learned, the paper was taken away and the test subject was re- /127
 requested to execute the series at a rate of speed convenient to him. The experimenter determined the average time of completion, and then this interval was used as a fixed time for completing the learned sequence of actions. The experimenter gave the signal to begin work by flashing one of the lights on the panel. The signal for the end of the time interval was given by flashing another light. The test subjects executed the sequence of actions 30-100 times.

The instructions informed the test subject that it was necessary to complete the learned series of actions within the time interval, which was delineated by two light signals. The start of the last (24-th) motion (key-pressing action) must coincide with the start of the last signal.

The experiments with the test subjects evaluating their own errors (4 test subjects) were carried out under the same conditions, but with the additional instruction that the test subject was to evaluate the accuracy of his work each time he had completed a sequence. The statements were to be "earlier" if he beat the terminating signal, "later" if he did not succeed in finishing within the appointed time, "exactly" if he considered that the start of the last action coincided with the work termination signal. The responses were recorded.

Indexes. The execution of the learned series of actions was recorded on the tape of a loop oscillograph at a tape speed of 4-10 mm/sec; when the tapes were examined with a photoamplifier, it was possible to evaluate the time intervals with an accuracy of 50-20 msec.

In analyzing the tapes we measured the time intervals, which made it possible to get a complete time scan of the process of executing a sequence of actions by the following scheme:

1	2	3	4	...	47	48	49	50
Latent period-time from the initiation of the start signal by the experimenter until the test subject started his first pressing action	Duration of the first pressing action	Pause between the 1st and 2nd pressing action (hand transfer time)	Duration of the second pressing action	...	Pause between the 23-rd and 24th action	Duration of the 24th action	Total time of completion (sum of Nos. 1-47)	Error (time discrepancy between the beginning of the 24th action and the issuance of the 2nd signal by the experimenter)

The measured intervals were calculated by row, each consecutive row corresponding to the next repetition of the sequence of actions in turn. Comparison of the magnitude and sign of the errors in each two adjacent rows of column 50 made it possible to determine whether there was error compensation relative to the prescribed time interval and how large the compensation was.

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Pairwise comparison of the values for the duration of the intervals in adjacent rows of columns 1-48 permitted determination of the distribution of the magnitude of the compensation over the entire time it took to complete the problem.

The difference in the prescribed time intervals was investigated for three test subjects.

Experimental procedure. A light was turned on in front of the test subject, sitting behind the panel, for a definite period of time (from 4-36 sec). The differences in the duration of the successively generated intervals were 1, 2, 4, 8, and 12 sec. The signals were supplied with an interruption of about 1 sec.

The test subject was requested to note the duration of the signal and to compare the duration of the prevailing interval with the preceding one. The estimate was announced with the words: "faster," "slower," or "the same." The instructions stated that it was not permitted to consciously count the time or to do anything else that would resemble such an action. The experiment was recorded continuously.

EXPERIMENTAL RESULTS

Magnitude of Errors and Degree of Their Compensation

In the main experiments 15 test subjects first solved the problem of keeping track of an interval. Each test subject repeated a sequence of actions in a given interval from 30 to 50 times.

In the secondary experiments 4 test subjects participated, each having experience in accomplishing the task of keeping track of an interval. Each repeated the sequence 90-100 times. In addition, in these experiments the test subjects had to make an estimate of how accurate their work was. Obviously, this facilitated a more effective solution of the interval monitoring problem. In this case the test subjects worked more accurately.

Of the 366 cases of repetition of the sequence in the secondary experiments, it was observed that errors, or deviations from the prescribed interval, were absent in 13 cases (3.6%). In 69 cases (18.9%) the error (on the lead or lag side) did not exceed 100 msec.

The mean value of the deviations from the interval was 260 ± 11 msec, which, in view of a specified of 13,00-1400 msec, does not exceed 2% of the error level.

In the main experiments (without estimating errors) tracking of the interval was less accurate. Given in Table 1 are data on the error distribution in this case (summed over the group of test subjects who completed the problem with a given interval of 15,000 msec; 8 people).

From the table it is evident that the greater portion of the errors (more than 60%), for both cases, lead and lag, lie within the range of 200-600 msec. The mean error for the case of lag was 726 msec, and for the case of lead it was 681 msec. At the given interval of 15,000 msec the average error was 4.8-4.5%.

TABLE 1. Relative Rate of Occurrence of Errors of Either Sign and Values for an 8-Man Group of Test Subjects

No. of cases	Error	Magnitude of error, msec						
		≤200	201-400	401-600	601-800	801-1000	1001-1200	1201-3000
Lag.....	294	0.14	0.36	0.15	0.13	0.07	0.05	0.10
Lead.....	195	0.17	0.23	0.21	0.09	0.07	0.09	0.14

Shown in Fig. 1 is the course of the interval-monitoring experiment for one of the test subjects. As evident from the figure, a continuous search is made during the experiment, with fluctuations on both sides of the interval. The extent of the fluctuations is relatively small; the majority of the deviations are compensated for in the next step (a deviation to one side alternates with a deviation to the other side). The shape of the curve is highly reminiscent of the fluctuation curve for an error-compensation feedback system.

In connection with the fact that the sequence of actions executed by our test subjects consisted of 24 uniform motor cycles and that the time of completion of the entire series, and not of only one cycle, was specified, we might ask what is the character of the distribution of the total time between individual cycles in the sequence of actions? We examined this question in [4]. In that investigation, in parts, we presented data obtained in experiments of the 1st series of the present report.

It was found that the overall time of fulfillment of a sequence is distributed uniformly over all 24 actions. In view of this fact it was conjectured that the uniformity of execution of a sequence of actions is governed by the operation of an internal generator which controls the time of completion of a single motor cycle.

A corollary of this hypothesis, which was confirmed in our experiments, is the argument that monitoring of a specified time interval must be attendant upon some sort of adjustment of the interval generator which controls the time of a motor cycle or, in other words, time is monitored by searching for the frequency of motion and monitoring this frequency. /130

The term "time monitoring" was introduced by M. A. Alekseyev [2] for cases when man must accomplish a certain task within time intervals controlled externally. Under such conditions, which prevailed in our experiments also, each person was required not only to accomplish the necessary actions in a required order, but also to space them out over a specified time interval in such a way as to cover the

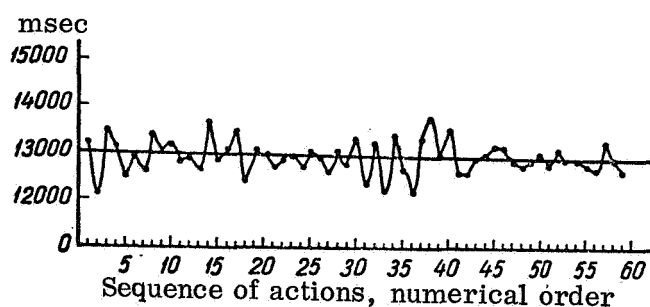


Figure 1. Monitoring of a Specified Time Interval (Test subject P-v). Horizontal Line-the Specified Interval (13,000 msec).

error was committed (the test of "appreciable" was a decrease in error of $\geq 30\%$ its magnitude).

Given in Table 2 are the composite data characterizing the dependence of the compensation rate on the magnitude and sign of the error for the group of test subjects who participated in the principal experiments.

TABLE 2. Relative Frequency of the Cases of Compensation or Aggravation of an Error as a Function of the Magnitude and Sign of the Error in the Preceding Repetition of the Sequence

Error category	Magnitude of the errors, msec						
	≤ 200	201-400	401-600	601-800	801-1000	1001-1200	1201-2000
Lag errors							
No. of cases	42	105	43	37	20	14	33
Compensation, % ...	19	36	40	43	70	71	70
Aggravation, %	62	37	33	11	15	7	6
Lead errors							
No. of cases	33	46	41	17	14	18	26
Compensation, %	30	55	47	53	50	83	81
Aggravation, %	42	21	34	17	21	6	4
Total	294						195

Presented in Fig. 2 are curves demonstrating the dependence of the magnitude of the compensation and of the aggravation of the error on the magnitude of the error.

As evident from the table and figure, there is a distinct relationship between the magnitude of the errors and the degree of its compensation. Clearly evident are three zones characterizing the degree of error compensation: deviations of less than 200 msec are practically uncompensated; deviations of 200-800 msec for the case of lag and of 200-1000 msec for lead are compensated in approximately

interval. It is only natural that in carrying out this task it is necessary somehow to keep track of the time. It is possible to find out precisely how this process is done by investigating the time-error compensation process. We carried out such an investigation by pairwise comparison of all cases when an appreciable decrease in error was observed in the repetition following the one in which an

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half the cases (zone of partial correction); deviations exceeding 800 or 1000 msec are compensated in the majority of cases (zone of satisfactory correction). A decrease is observed in the number of cases of error aggravation as the number of errors increases.

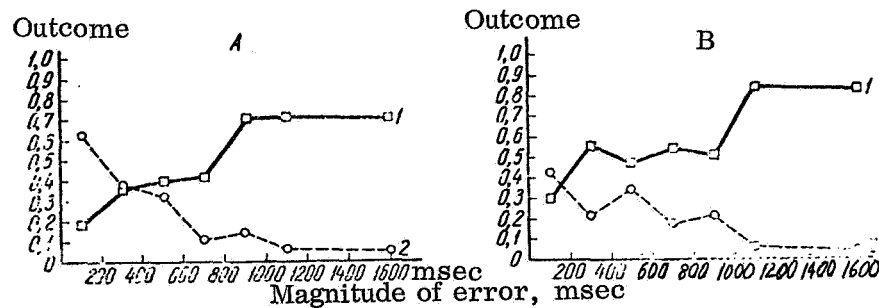


Figure 2. Probability of Compensation (1) or Aggravation (2) of Error in Completing a Sequence of Actions as a Function of the Deviation from the Specified Interval in the Preceding Repetition for the Cases of Lag (A) or Lead (B).

Thus, the phenomenon of error compensation is related to the magnitude of the deviation from the specified time. On the other hand, the character of the curves showing an increase in the number of compensated errors for errors of different sign (lead and lag errors) reveals a distinct similarity and indicates that the phenomenon of error compensation does not depend on the sign of the error.

Character of Error Compensation

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Since we have no knowledge whatever of the distribution of error compensation over the time of completion of a sequence, of the dependence of this distribution on the sign of the error, or on its magnitude, we attempted to examine this question from these viewpoints. Given in Table 3 is an analysis of 240 cases of compensation (all cases where the error was sufficiently large and its compensation was complete and distinct); the method of pairwise comparison of intervals was used to establish the differences representing a measure of the extent to which individual time segments of the sequence participated in compensation. Considered in the table are the dependence of the character of the compensation on the sign of the error and the three methods of compensation to which all the the examined cases reduced. Special attention was devoted to the differences in the first time segments of completion of the sequence.

The reason why we proceeded in this fashion was that we expected two possible analytical results:

1) error compensation is accomplished as a result of a difference in latent period or in the initial time of completion; the overall tempo of completion will not be changed (the case when the internally controlled interval does not take on a new value);

2) error compensation is uniformly distributed over a large number of motor cycles (the cases when the internally controlled interval takes on a new value).

From Table 3 the following is evident:

1) the character of the compensation and its distribution are approximately the same for errors of either sign;

2) the latent period and the start of execution of a sequence are not the most responsible for compensation of the execution of a sequence by sections;

3) error compensation is uniformly distributed either over the entire period of the sequence or over approximately half the period of the sequence;

4) half of all cases are made up of compensation uniformly distributed over the entire sequence of actions.

It must be noted that the sum of the differences in the intervals given in each row is less than the total magnitude of the compensation, since values representative of the last three actions of the series are absent. The time of completion of these actions was not taken into account because this time may have been affected by the signal for termination of the given interval and is superimposed on the compensation of the preceding error. Therefore, the column "first half of the sequence" includes the time of completion of the 4th to 12th actions, while the column "second half of the sequence" includes that of the 13th to 21st actions.

In view of the fact that the compensation method as well as the very circumstance that compensation occurred proved to be independent of the sign of the error, composite data on compensation, ignoring the sign of the error, will be given in the rest of the presentation.

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Since the case of uniform distribution of compensation over the entire period of the sequence of actions is of the greatest interest for purposes of determining changes in the value of internally controlled intervals, the subsequent analysis of the distribution of differences was carried out on the basis of precisely three cases. We analyzed 111 cases of uniform distribution of error compensation (Table 3 contains a total of 125 such cases, but in 14 cases we detected technical defeats in the records which prevented inclusion of these cases in a more detailed analysis). The entire sequence of actions was divided into 4 equal segments of 6 actions each; analyzed were the pairwise differences in each of the segments, then one of these segments (the second in the sequence) was analyzed with respect to each of the smallest segments of execution, i.e., with respect to all the pressing times and all the pauses between consecutive motions.

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We computed the differences in time of completion in each of the segments; the first segment belonged to performance with an error, the second to performance with error compensation (Table 4, A, B).

As evident from the tables, the total value of compensation is distributed uniformly over the entire time of completion of a sequence, even down to change

TABLE 3. Distribution of Error Compensation with Respect to the Time of Completion of a Sequence

Character of compensation	No. of cases	Magnitude of the error msec	Magnitude of the compensation msec	Magnitude of difference in various execution intervals, msec			
				Latent period	first three actions	first half of sequence	second half of sequence
Lag error							
Uniform over the entire sequence	65	977 ± 96	1323 ± 66	87 ± 28	144 ± 30	547 ± 21	542 ± 50
Uniform in the first half of the sequence	41	628 ± 87	992 ± 155	112 ± 33	163 ± 57	844 ± 149	-233 ± 83 *
Uniform in the second half of the sequence	25	1192 ± 252	1370 ± 235	70 ± 40	12 ± 61	-14 ± 123 *	1262 ± 197
Lead error							
Uniform over the entire sequence	60	845 ± 95	1196 ± 124	37 ± 17	152 ± 30	466 ± 71	547 ± 78
Uniform in the first half of the sequence	27	793 ± 140	743 ± 82	124 ± 34	180 ± 34	642 ± 109	-226 ± 73 *
Uniform in the second half of the sequence	22	993 ± 119	1041 ± 139	59 ± 37	77 ± 28	-103 ± 43 *	1082 ± 133

*Cases when the error is aggravated rather than being compensated.

TABLE 4 (A). Distribution of the Magnitude of Compensation Over Segments of the Sequence (111 cases) (Mean Value of the Error, 892 msec; Mean Value of the Compensation, 981 msec)

Segments of the sequence	Magnitude of compensation (msec)	Fraction of the total value of compensation	Error residue after compensation by the respective segments
I (motions 1-6)	305	0.3	587
II (motions 7-12)	265	0.27	322
III (motions 13-18)	268	0.28	54
IV (motions 19-24)	148	0.15	-94

TABLE 4 (B). Distribution of the Magnitude of Compensation Over the Time of Execution of Motor Cycles and Their Elements in the Second Segment of the Sequence (111 cases)

Numerical position of the motor cycle in the sequence	Magnitude of the compensation for cycle (msec)	Fraction of the compensation of the entire segment	Magnitude of the compensation for pressing time (msec)	Magnitude of the compensation for the pause between pressing actions (msec)
7	41	0.15	18	23
8	30	0.1	15	15
9	65	0.24	20	45
10	55	0.2	12	43
11	34	0.11	16	18
12	40	0.15	15	25

in the value of the duration of each pressing action and of each pause between consecutive actions. Particular attention should be paid to the high uniformity of these changes, indicating that the error compensation mechanism is incident to variation in the mean value of the interval during which one motor cycle is completed. In the light of what has been previously said, this means that the mechanism controlling the speed of motion (the interval generator) is responsible for compensation. In this connection the mean value of compensation for one motor cycle is deserving of attention. From the data given in Table 4 (B) it is not difficult to compute that the mean value of the change in interval of a motor cycle is 44 msec. Let us note this figure and go on to consider the question of the dependence of the compensation method on the magnitude of the error. As has already been said, analysis resulted in the discovery of three possible methods, covering the majority of cases: 1) uniform compensation, when the magnitude of the error with a minus sign was equally distributed over all the motor cycles falling within the time of execution of the sequence during which the preceding error is compensated; 2) compensation of the first half, when complete error compensation was accomplished already halfway through the next sequence, and then compensation stopped; 3) compensation of the second half, when the rate of execution of the first half of the sequence, all of which was taken up by error correction, did not differ from the rate of execution of the

preceding (error-generating) run, and in the second half a sharp shift occurs, leading to compensation at the end of the period.

All the cases referring to one or the other of the compensation methods were broken down into groups as a function of the magnitude of the error, and their mean values were computed. The groups were associated with errors of the following values: 1) large errors (about 2,000 msec); 2) moderate errors (about 1,000 msec); 3) small errors (about 500 msec). The results of the analysis are given in Tables 5, 6, 7. The tables were compiled as follows: after the errors had been arranged in groups, we averaged the pairwise time differences of 12 segments between the sequences in which the working speed gave rise to the error and the next sequence in which the error was compensated. These differences were represented as the total residue of the error after completing the given segment of the sequence. /137

The speed of completion of the segment may be the same as in the preceding sequence (if so the magnitude of the error residue remains unchanged), may change in favor of error compensation (magnitude of the error compensation decreases) and, finally, may change in favor of error aggravation (magnitude of the error residue increases). In the right-hand columns of the tables these quantities are expressed in %. The total magnitude of the error (regardless of its specific value) is taken as 100; the attainment of complete compensation as 0; quantities with a "minus" sign reflect the process of overshoot of zero and accumulation of an error of the opposite sign.

The following is evident from these tables: /138

- 1) the decrease in error during the compensation process is a slow affair and is attendant upon the completion of no less than one half the sequence of actions during which compensation takes place;
- 2) when the errors of various gradations (large, medium and small) we run up against all the enumerated compensation methods;
- 3) when estimating errors as percentages (when the magnitude of the error is leveled off) it is found that the compensation method has approximately the same characteristics (Table 5, lines 1-6; Table 6, lines 1-6 and lines 9-11; Table 7, lines 7-11).

Of the greatest significance is the fact that all three compensation methods were found for errors of the various magnitudes, indicating that the compensation method does not depend on the magnitude of the error.

Shown in Fig. 3 are graphic representations of the above-mentioned three error-compensation methods, regardless of the magnitude of the error (we took the average values of the percentages of errors in Tables 5, 6, and 7 for errors of the various groups). Deserving of attention is the change in nature of the curve during the process of compensation, and is especially noticeable in the case of compensation in the first half.

This change testifies to the change in working speed (readjustment of the interval being controlled) during the execution process and raises the question of

TABLE 5. Distribution of Error Compensation Over the Time of Completion of Individual Motor Cycles as a Function of the Magnitude of the Error

Magnitude of the errors at various times during the the correction process	Large errors (msec)	Medium errors (msec)	Small errors (msec)	Large errors %	Medium errors %	Small errors %
Magnitude of the error	1960	1100	555	100	100	100
Residue after compensation in the latent period + cycle 1	1740	860	400	89	78	72
Residue after compensation in the latent period + cycles 1, 2, 3	1490	825	350	76	75	63
Residue after compensation in the first five cycles	1250	715	250	64	65	45
Residue after compensation in the first 7 cycles	1050	610	130	54	56	24
Error residue after 9 cycles	890	470	55	45	43	10
Error residue after 11 cycles	675	350	-95	34	33	-17
Error residue after 13 cycles	512	250	-225	26	23	-41
Error residue after 15 cycles	40	262	-330	2	24	-60
Error residue after 17 cycles	-75	135	-305	-4	12	-55
Error residue after 19 cycles	-87	-50	-480	-5	-4.5	-87
Error residue after 21 cycles	-240	-240	-570	-12	-22	-103
Error residue after 23 cycles	-100	-150	-440	-6	-14	-79
Total magnitude of the compensation in 23 cycles	2060	1250	995	106	114	179
Average value of the compensation for one motor cycle (msec)	83	50	40			

the criteria by which man is guided in the running process of monitoring his working speed. The inflection point on this curve lies below the zero line. This may mean in the evaluation by man that the corrections he introduced into the speed of execution are too large and he begins to reduce them.

Now let us return to the magnitude of the compensational increment per motor cycle. Above we wrote that the average increment (for errors of the

TABLE 6. Distribution of Compensation Over the Time of Completion of a Sequence in Those Cases When Correction Predominated in the First Half of the Work Period

Magnitude of the error at various instants of the correction process	Medium errors (msec)	Small errors (msec)	Medium errors (%)	Small errors (%)
Magnitude of the errors	1080	450	100	100
Residue after the latent period + cycle 1	620	330	57	73
Residue after 3 cycles	455	285	42	63
Residue after 5 cycles	255	225	24	50
Residue after 7 cycles	115	100	11	22
Residue after 9 cycles	-145	-15	-14	-3
Residue after 11 cycles	-270	-30	-25	-7
Residue after 13 cycles	-395	-50	-37	-11
Residue after 15 cycles	-345	-75	-31	-17
Residue after 17 cycles	-420	-45	-39	-10
Residue after 19 cycles	-420	-70	-39	-16
Residue after 21 cycles	-435	-55	-40	-12
Residue after 23 cycles	-300	-15	-28	-3
Total magnitude of compensation in 23 cycles.....	1380	465	128	103
Average value of the compensation per motor cycle	80	43		
	(cycles 2-13) (cycles 2-9)			

various magnitudes and for uniform compensation) is 44 msec. From Table 5 it can be seen that the average values of the increment for various cases are 83, 50 and 40 msec with uniform compensation, where 83 msec is the increment for compensating large errors, 50 for medium deviations and 40 for small deviations. The magnitudes of the increment were computed in Table 6 for the same part of the curve that reflects a shift in compensation. For this purpose we took the maximum magnitudes (from 1,080 msec for medium errors of the total magnitude of the error up to 395 msec of the opposite sign, i. e., points where curve inflection began) and the total magnitude of the compensation was spread over the number of cycles in which compensation occurred.

It was found that the shifts for one cycle amount to 80 and 40 msec. Shifts for a single motor cycle were obtained in the same way from Table 7. From the table it is evident that for various gradations in the values of the error these shifts amount to 136, 84 and 45 msec. Thus, the increments reduce in all cases to three values: 1) 40-45; 2) 80-84 and 3) 136 msec. Perhaps it is not accidental that the magnitude of the increment in the second and third gradations corresponds to double and triple the value of the smallest increment.

To solve the question of the mechanisms responsible for compensation of the deviation from the given time, it is useful to clarify the part played by human evaluation mechanisms relative to errors themselves and to time intervals.

TABLE 7. Distribution of Compensation Over the Time of Completion of a Sequence
in Those Cases When Correction Predominated in the
Second Half of the Work Period

Magnitude of the error at various instants of the correction process	Large errors (msec)	Medium errors (msec)	Small errors (msec)	Large errors (%)	Medium errors (%)	Small errors (%)
Magnitude of the errors.....	2125	1120	530	100	100	100
Residue after the latent period + cycle 1	2175	1330	530	102	119	100
Residue after 3 cycles	2155	1300	480	101	116	91
Residue after 5 cycles	2100	1380	510	99	123	96
Residue after 7 cycles	2050	1300	540	96	116	102
Residue after 9 cycles	2075	1210	530	98	108	100
Residue after 11 cycles	2025	1100	520	95	98	98
Residue after 13 cycles	1925	1020	360	91	91	68
Residue after 15 cycles	1600	750	360	75	67	68
Residue after 17 cycles	1050	740	310	49	66	58
Residue after 19 cycles	750	630	270	35	56	51
Residue after 21 cycles	300	550	80	14	49	15
Residue after 23 cycles	175	100	-20	8	9	-4
Total magnitude in 23 cycles	1950	1020	550	92	91	104
Average value of the compensation per cycle (from the 10th to the 23rd).....	136	84	45			

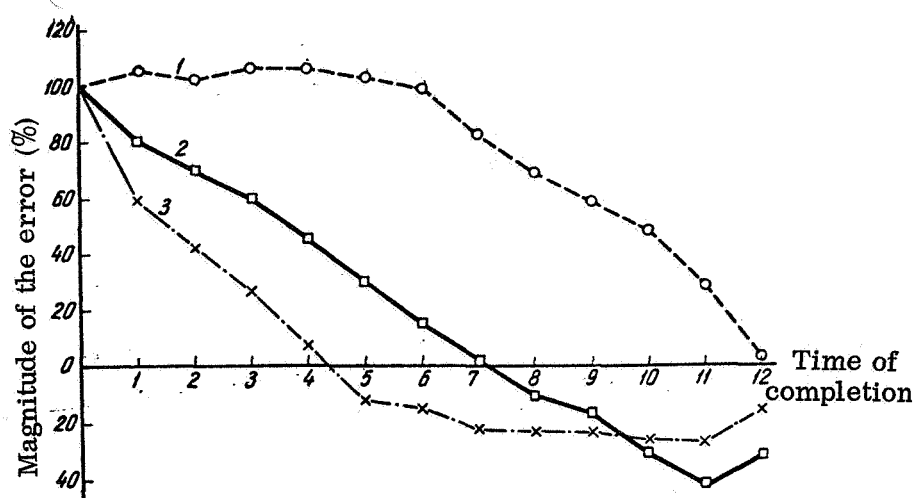


Figure 3. Character of the Compensation of Deviations from the Prescribed Interval (distribution of the increment which corrects the error over the time of the next repetition after the error):

1—Compensation in the Second Half of the Sequence; 2—Uniform Compensation; 3—Compensation in the First Half of the Sequence.

Error Estimation (deviations from the prescribed interval)

As already mentioned above, in these experiments four test persons repeated a large number of times (90-100) the well-known (to them) problem of 24 key-pressing actions on a panel within a given time interval (13.0-14.0 sec). After each repetition they estimated the degree of coincidence between their work and the time-controlling signal (remember that complete agreement required coincidence between the start of the 24th pressing action and the signal announcing the end of the given segment).

A correct estimate of a deviation error was considered to be a recognition of the sign of the error (in terms of "ahead" and "behind"). While recording the working time on the tape the error was measured and compared with the estimate. The results of this comparison are presented in Table 8, which contains the frequency of the correct estimates as a function of the magnitude of the deviation. In all 351 cases from 364 measurements were examined in the table. An absence of deviations was observed in 13 cases, and therefore they were not entered in the table.

To evaluate the significance of the figures given in the table, it is necessary to keep in mind that the test subject had the capability of choosing one of three responses.

Hence, in a completely random process, when the test subject does not discriminate between the presence or absence of an error, three equally probable

responses exist ("exactly," "behind," and "ahead"), one of which proves to be correct. Therefore the frequency of correct estimates up to 33% must be considered as the level of absence of correct estimates and only large frequencies need be taken into account. Within such a framework of reference, it is evident from Table 8 that errors of up to 100 msec are not evaluated by the test subjects. Errors of 100-150 msec are possibly evaluated. It is even more probable (62% correct estimates) that errors of 150-200 msec are evaluated, and all errors of 200 msec and greater are correctly estimated in all cases. Thus, it can be considered that the magnitude of 150-200 msec is the threshold for estimating mismatch errors between the actions themselves and the given time. This magnitude is considerably lower than the one at which error compensation is good (800-1000 msec, when the error compensation reaches 70-80%; Table 2). This means that the compensation threshold and the estimation threshold do not coincide, and the mechanism of estimating mismatch errors cannot be the only factor responsible for error compensation.

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TABLE 8. Estimation of Characteristic Errors as a Function of the Magnitude of the Deviation from the Given Interval

Magnitude of the deviation (msec)	Number			Magnitude of the deviation (msec)	Number		
	Cases	Correct estimates	Correct estimates in % of the no. of cases		Cases	Correct estimates	Correct estimates in % of the no. of cases
20-100	68	15	22	201-300	78	78	100
101-150	45	20	44	301-500	60	60	100
151-200	49	39	62	above 500	51	51	100

Estimation of Differences in Intervals

In view of the fact that the literature contains data relating to the dependence of the threshold of time-interval discrimination on the magnitude of the intervals [3], our experiments on discrimination of intervals were set up in the following manner. Intervals of 8, 16, and 24 sec were taken as the initial intervals relative to which discrimination was determined. The discrimination thresholds were examined in these limits in order to be able to analyze them both in terms of absolute value (in sec) and infractions of the initial interval. For this purpose, in the 8-sec interval we used comparison intervals differing by 1, 2 and 4 sec, both on the greater and smaller sides. In the 16-sec interval, intervals differing by 1, 2, 4 and 8 sec from the original (on both sides) were used for discrimination. For the 24-sec interval we used differences of 1, 2, 4, 8 and 12 sec on both sides. The intervals were prescribed by a device which made it possible to turn on a continuous light signal of the given duration, the error not exceeding 10 msec.

Each time the appropriate signal was given, the test subject had to compare it with the preceding one and make one of three responses relating to how he estimated the comparison (equal, shorter or longer). The results of this experiment

are given in Figs. 4 and 5, which contain 143 estimates of the above-described intervals by three test subjects.

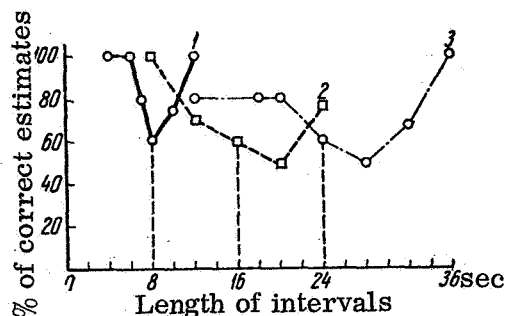


Figure 4. Discrimination of the Lengths of Intervals as a Function of Their Original Value.

Discrimination of Intervals as Compared with Intervals of 8(1), 16(2), and 24 sec (3).

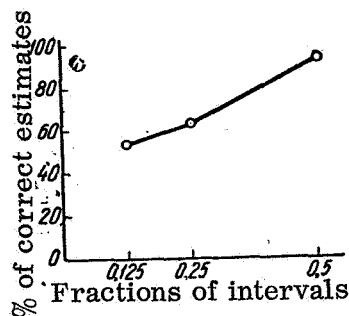


Figure 5. Discrimination of the Lengths of Intervals for Differences of $1/8$, $1/4$, and $1/2$ of the Original Intervals.

From Fig. 4 it is evident that the 8-sec interval is distinguished from the 6-sec and 10-sec in 100% of the cases.

The curve has a sufficiently steep slope on both sides. At the 16-sec interval the discrimination curve has a more diffuse character; 100% of the correct comparison estimates were observed only in the case of decrease of this interval by 8 sec; 80% correct estimates were observed when the interval was increased by the same amount. The 24-sec interval was not so well distinguished from larger and smaller intervals as the preceding ones. The discrimination curve is spread out; 100% discrimination was observed when the interval was increased by 12 sec; 80% correct estimates were observed when the interval was decreased by 12 sec.

These results forces on us the idea that the threshold for distinguishing the length of a signal depends on the absolute value of the signal. In all cases when the interval being compared differs by $1/2$ from the original interval, discrimination between the two intervals is good. This relationship is true for all three of the intervals used and is shown in Fig. 5, which presents data on the discrimination of two intervals, summed for all cases, where the difference between the compared intervals is expressed in fractions of the original interval.

Since all the preceding experiments were performed primarily at intervals close to the 16-sec interval, it is precisely this interval which is of greatest interest to us. From the curve in Fig. 4 it is evident that discrimination of intervals differing by 2 sec amounts to 40-70%, while complete discrimination is observed at a difference of 8 sec. At the same time, as we wrote earlier, complete error compensation with respect to the specified interval, when rhythmic activity is carried out during this interval, is observed when the deviation is about 1 sec. Thus it is doubtful whether the mechanism by which the length of a specified interval is estimated participates in error compensation.

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CONCLUSION

The data obtained in our experiments concern the problem of regulating the time characteristics of motion in man. In particular, they yield grounds for discussion of two questions:

- 1) possible interpretations of the fact that an error relative to a specified interval is compensated;
- 2) consequences ensuing from the qualitative characteristics of compensation.

Let us consider the experimental results in the light of the first question. It has been demonstrated that man executes a sequence of 24 actions while adhering to a specified (fixed) time interval and not deviating from this interval by more than 2-5%. It has also been demonstrated that errors of this dimension are compensated in the next repetition of the sequence. The overall time pattern (rhythm) of execution of the sequence remains constant under these working conditions, a fact which was examined in detail in some of our other papers.

Moreover, in this situation there exists a certain fixed interval for execution of a single motor cycle, the values of this interval changing by no less than 40-50 msec during compensatory adjustments. This implies that we are dealing here with three levels of the control process:

- 1) adjustment of the execution of the entire motor problem to an externally prescribed time interval;
- 2) control of the intervals of segments of the problem in conformity with a problem stored in the memory (execution of a program of ordered actions);
- 3) control of the frequency of responses, resulting in overall compensatory adjustment of the entire time of execution.

Only the first of these levels deals with an external, time-gauging signal; the remaining two are obviously connected with the operation of interval mechanisms of the central nervous system which measure and specify the frequency and rhythmic pattern of individual motor cycles.

It is natural to assume that the described levels do not cover the entire list of /144 levels in controlling the time characteristics of motion.

Here we are dealing with high control levels which issue general, undetailed instructions. Completely outside the framework of our examination are such levels as instructions on the speed of hand transfer in a direction toward the key to be pressed and in the reverse direction or instructions on the time correlation of contraction of individual muscles, or, finally, control of the time characteristics of individual motor acts.

The facts we have discovered relating to error compensation with respect to a specified interval and to compensatory adjustments affecting each motor cycle more or less uniformly permit us to draw some conclusions as to the characteristics of the processes underlying the above facts in the light of the theory of servosystems.

Application of this theory to the effector activity of man has been examined in detail by Adams [8] who believes that any human activity oriented toward eliminating errors of mismatch with an externally specified signal is a servosystem activity controlled over feedback channels by the magnitude of the mismatch error. At the same time Adams distinguishes between one- and two-dimensional monitoring systems, meaning by the latter, systems which are required to monitor two independent signal sources. Two-dimensional tracking systems are complex (especially in cases of bisensory tracking) and have hardly been studied.

Within the framework of these viewpoints, the problems of our test subjects are viewed as problems of monitoring a specified interval. The experimentally obtained characteristics of error compensation induce us to believe that we are dealing with a two-dimensional monitoring problem. The fact is that the test subjects accomplished error compensation by changing the frequency of the motor cycles. In order to do this it is necessary to fix in the memory not only the dimension of the given interval, but also the frequency of one's own motions. Consequently, the input of the given servosystem must be supplied with two signals; 1) the signal of mismatch in the time of completion of the last action and the end of the specified interval, and 2) the value of the frequency of the responses, on which depends the total time of execution; the detected mismatch with the specified interval.

The second question which it is expedient to discuss in connection with the results of our experiments deals with compensation mechanisms, in the light of establishing a link which is most responsible for this process. In the experiments it was determined that the thresholds of estimation of errors, of error compensation, and of discrimination between specified intervals do not coincide. Personal error is detected at a magnitude of 150-200 msec, is compensated at a value of 400-1000 msec, and the specified interval is distinguished from a different size interval at a difference of 4000-8000 msec. It must be imagined that neither an estimate of personal error nor an estimate of the specified interval as a whole can be the solely responsible links in the compensation process. The necessary missing link is a system which evaluates and controls the frequency (speed) of motion.

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The literature contains a considerable quantity of data testifying to the fact that the personal frequency of motion is controlled and is conducive to accuracy in executing the motor problem [9, 12, 13, 15]. On the other hand, some authors assert that control of the time distribution of responses is due completely to externally provided signals [2].

It is believed that there will be good agreement between the various viewpoints if the ideas we presented are accepted, namely, two-dimensional monitoring of signals carrying information about time, of the external signal, and of the frequency of personal motions.

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CHARACTERISTICS OF THE BIOMECHANICS OF ELEMENTARY
HUMAN MOTION UNDER THE CONDITIONS OF
WEIGHTLESSNESS AND G-LOADING

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The aim of the present investigation is to clarify the differences in the coordination structure of the simplest human motor skills in a variable gravity field (from 0 to 20 g).

The study of the coordination structure of motion was carried out by means of the cyclogrammetric method developed by N. A. Bernshteyn [3].

In our research we made photographs, in profile, of the moving arm, to which three small electric lights were attached, the first near the first phalanx of the second finger of the right hand, the second at the level of the radiocorpal joint, and the third at the level of the elbow joint.

An obturator with four slits was set up ahead of the camera and was driven at a uniform rate of rotation by a small electric motor. The speed of obturator rotation was chosen to be such that the time intervals for fixation of arm sections was 64 per sec. Photography yielded negatives with discontinuous traces of the path of motion of the given part of the arm.

A sample of these paths is given in Fig. 1. For convenience in determining the specific coordinates of points on the paths, a scale grid was imprinted on the photographic record, which made it possible to determine the coordinates with an accuracy of up to 1 mm. If we consider that the difference in value of the coordinates of consecutive points (the first derivative), referred to time, shows up in the abscissa or ordinate as the velocity component of displacement of the given arm section, while the difference in value of the first differences (second derivative), again referred to time, is the acceleration, it is necessary to introduce the mass of the given part of the arm into the equation in order to determine the force applied to this part at a given instant.

The weight of the arm part is added to the inertial force obtained as a result of the above computation in order to get the vertical force component. In our investigations the weight is left out in all cases of weightlessness, but is added in increasing magnitude in conformity with the load applied. /147

The data were analyzed directly from parametric graphs of the velocity, acceleration - and force - components and, less frequently, by constructing the total vectors of the forces applied to the center of gravity of the different parts of the arm in some of the more important attitudes assumed in executing the motion being analyzed.

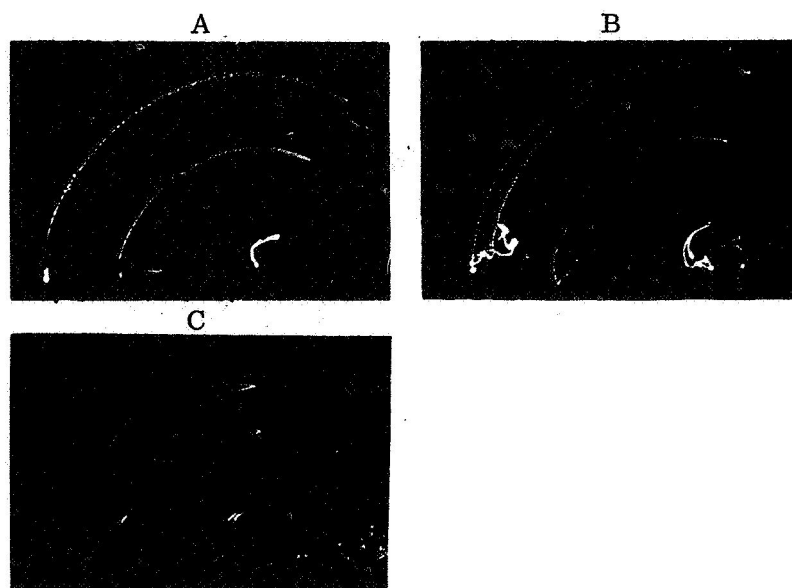


Figure 1. Displacement of the Arm of a Man at the Elbow Joint During Flexure and Extension in a Normal Gravity Field (A), Under a Load of 2 g (B) and During Weightlessness (C):

1—Path of the Light on the First Phalanx of the Second Finger;
2—Path of the Light at the Radiocarpal Joint; 3—Path of the Light at the Elbow Joint.

The reason for doing this was that all the tiniest breaks (so-called "waves") are clearly traced on the parametric graphs. The breaks are peculiar, in some form or other, to a specific motion and are different in origin.

N. A. Bernshteyn [3] established three categories of such waves:

a) spontaneous - enervation waves, straightforwardly reflecting concrete nerve pulses and causing the formation of those components of the coordinational structure of motion that Chkhaidze called fundamental or dominant [5];

b) reactive waves of peripheral origin, reflecting displacement of parts of the body and causing the appearance, in the coordinational structure of motion, of forces which Chkhaidze called satellite;

c) waves of mixed origin, the reactive - enervational taking the intermediate position. They reflect both direct nerve pulses and reactive forces taking place on the periphery. According to Chkhaidze, the components of the coordination structure due by these waves are called secondary.

The present investigation was made by comparative analysis of the nature and origin of these waves when motions are executed under the conditions of weightlessness (20 sec) and with positive stresses of 1.8 to 2.2 g (10-12 sec) produced during flight of an aircraft along a Kepler curve. The various motions were

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flexure and extension (at the elbow joint) of a free arm over a period of 2.0 sec; the same motions with the arm loaded (dumb-bell weighing 3.0 kg); flexure and extension of a free arm over a period of 0.5 sec; and directed extension (striking an indicated point with a finger) for 0.3 sec.

Four men, aged 25-35, took part in the investigations. The total number of processed photographic records was 25.

RESEARCH RESULTS

Despite the apparent simplicity, the coordinational structure of the motions are studied is sufficiently unusual, even when executed under the normal gravitational effects of the earth, and obeys specific laws.

When a free or loaded arm is slowly flexed at 1 g (Figs. 2 and 3), the curves of the force components at the start of motion form characteristic peaks $n\gamma$ in the longitudinal components and nA in the vertical ones. As a result of addition of these forces, the total vectors applied to the center of gravity of the arm sections assume the direction which is necessary to impart the appropriate motion to the arm (Figs. 2 and 3, positions I and II). It is completely natural that the magnitude of these vectors in flexure of the loaded arm is somewhat greater than in the case of the free arm. Since the given part of the motion depends entirely on its intended task, the two indicated peaks must be attributed to spontaneous - enervational waves. Then several new breaks appear in the curves. They are denoted as A^1 along the vertical and γ^1 along the longitudinal components. These reactive waves are caused by mechanical reaction of the periphery to the start of motion. Following this, the longitudinal force component drops below zero (the vertical component remains at the same value after a small peak nA), where a small decelerating wave Δ forms. As a result, the total force vectors abruptly reverse direction and, even though flexure is still far from being terminated, begin to decelerate motion of the parts of the arm (Fig. 2, position III).

But there is nothing surprising in this, since the impending complete change in the direction of motion (changeover from flexure to extension) requires a preliminary attitude. Since it is first necessary to overcome inertia of the members, the decelerating forces appear long before flexure is completed. One of the proofs of the validity of what has been said is that when the loaded arm undergoes flexure, vector reversal begins somewhat earlier than in the unloaded case (in position II, and not in III; see Figs. 2 and 3). /149

What has been said gives a good illustration of the autonomy of the activity of an internal habit control loop, which is realized without any intervention by higher organs of the central nervous system, and, in particular, of the consciousness. /150

Complete deceleration of parts of the arm is followed by a smooth transition to extension, smooth because of prior deceleration. This is accompanied by the appearance, in the force components, of new spontaneous enervational waves ϵ over the longitudinal terms and B over the vertical ones. Both are clearly evident and thanks to them forward and downward motions are imported to the hand and forearm. There is no doubt whatever as to their origin, since they are completely subordinate to the consciousness of /151

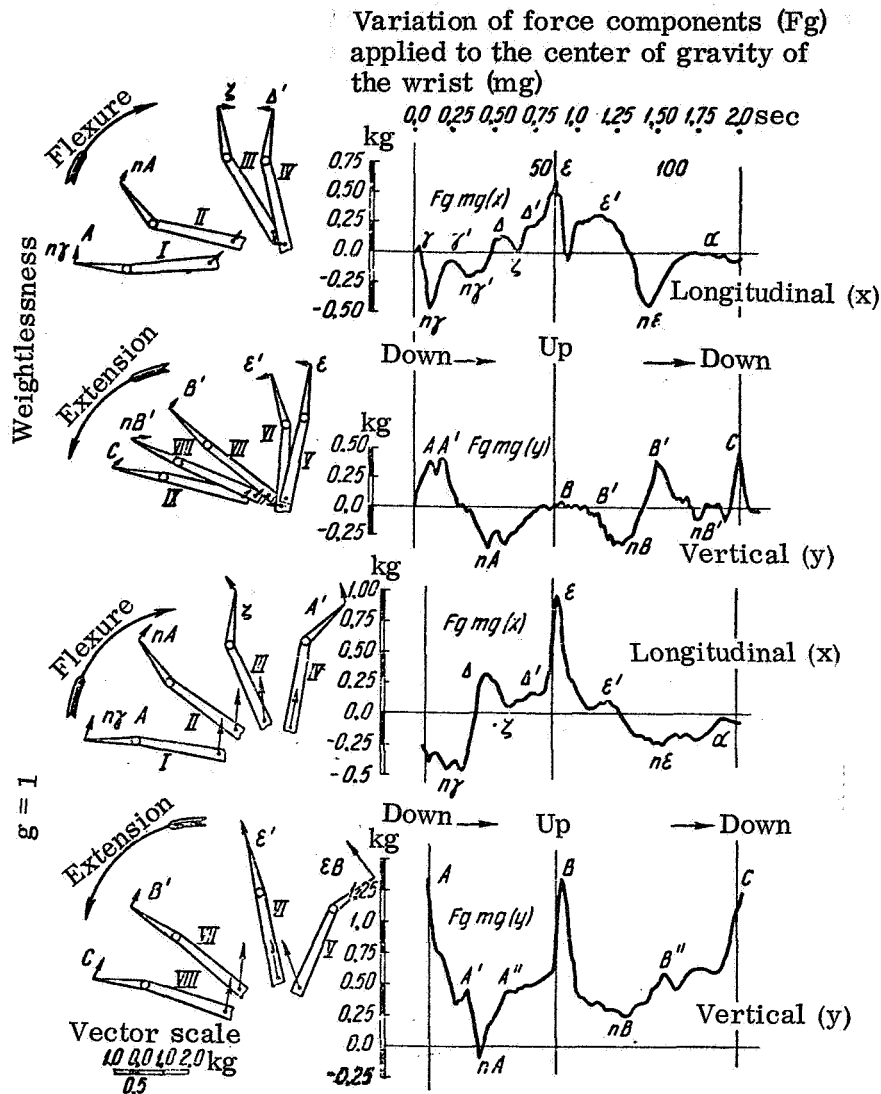


Figure 2. Coordination Structure of Slow Flexure and Extension of a Free Arm at 1 g and During Short-Term Weightlessness (above).

the human executing the motion. As a result of summing forces reflected by these waves, the vectors applied to the centers of gravity of the hand and forearm take on the direction necessary for the start of extension (position IV, Figs. 2 and 3).

The start of this motion is characterized by an abrupt fall-off of both the force components, a small break, a satellite of the wave ε , which we denoted by ε' , being traced along the longitudinal components.

The occurrence of this break has a fundamental nature. There is reason to believe that this is a correction signal from the inner loop which controls habits. This idea is proved to a known degree by the fact that it appears 0.12-0.14 sec after complete evolution of the main wave. As Chkhaidze and Gurfinkel have

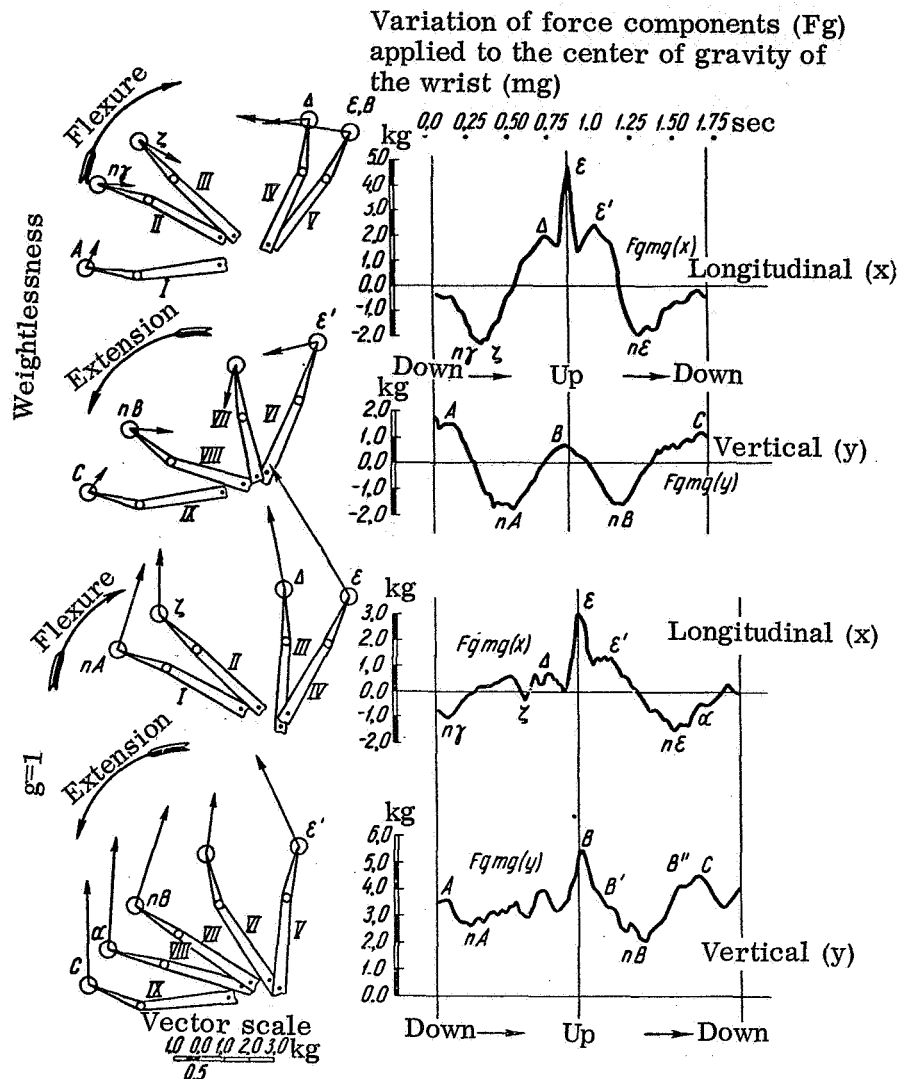


Figure 3. Coordination Structure of Slow Flexure and Extension of a Free Arm at 1 g and During Short-Term Weightlessness (above).

shown, the most important correction signals of this loop, so necessary to get the correct course of motion, occur at approximately the same frequency [2, 6, 7]. After the motions have completely evolved, the longitudinal force components again return to zero (the wave $n\epsilon$), thus again generating deceleration forces which are necessary to stop the arm in executing a motion. As a result, the force vector again takes on a direction counter to the course of motion (Figs. 2 and 3, positions V, VI, VII). When the loaded arm completes extension, this vector is not only appreciably greater in magnitude than in the free case, but also assumes the required direction somewhat earlier (almost at the very beginning of extension, position V).

Before the arm stops, and consequently somewhat before the main decelerating force C develops in the vertical components, the satellite reactive wave B

shows up clearly in the components. This is the second (now extensional) reaction of the periphery to hand motion.

The motion terminates with complete development of the auxiliary reactive-enervational force C and resultant stoppage of the arm.

The realization of the above-described motions by the free arm, with a jerk, in 0.5-0.75 sec results in a certain reorganization of the structure of habitual motion. In particular, as shown by the lower part of Fig. 4 (right-hand side), the wave n_y over the longitudinal components merges with the wave n_x , but the satellite of the wave A; the break A', is absent. The decelerating force Δ is not very pronounced. But the characteristic return of the longitudinal components to zero, as evident from the left side of Fig. 4, permits the force vector to assume the direction necessary for timely deceleration. In this case, in complete agreement with the laws of mechanics, this situation sets in considerably earlier than in executing the analogous motion at a low speed (Figs. 2 and 4, position III). Despite the high speed of arm motion, the correction signal ε' still appears at the very start of extension and when extension takes place with a rush, but because the motions merge somewhat, the curves have somewhat fewer breaks. In particular, the characteristic reactive wave B is absent.

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Our reason for executing purposeful extension motion was to trace how its structure changes when it is determined by a distinct meaningful task.

Figure 5 (the lower part) gives an overall picture of this motion. The first part, preparatory flexure, is in no way different from the abrupt flexure described above, but the second extension, which is carried out also in less than 0.5 sec, is interesting in that very distinct satellite waves ε and B' are observed in both the longitudinal and vertical force components. These are important correctional signals. It is easy to see that the execution of purposeful extension required rapid and distinct corrections and they appeared in the form of satellite waves. It is possible that in the given case they are of the spontaneous-enervational character.

If we return to Fig. 1, it is not difficult to recognize that the structure of habits under different gravitational conditions cannot be identical.

Even the external picture of the path of motion of recognizable points of the arm in executing such relatively simple habitual actions as slow flexure and extension is different.

Even though the hand and wrist move under the effect of normal gravitational force in such a way that the paths of flexure and extension practically coincide, in weightlessness and under positive loads the arms move along one path when being raised and along another when being lowered.

This is true because, on the one hand, the elbow of the test subject was not fixed in any special way, since this was not envisioned in the problem of motion. On the other hand, according to N. A. Bernshteyn's opinion, which he stated in discussing the data, when $g = 0$ the greater part of the muscular forces which were used earlier (at 1 g) to dampen the reactive and other force components was liberated; this also contributed to the differences in the path of motion for flexure and extension which are characteristic of weightlessness.

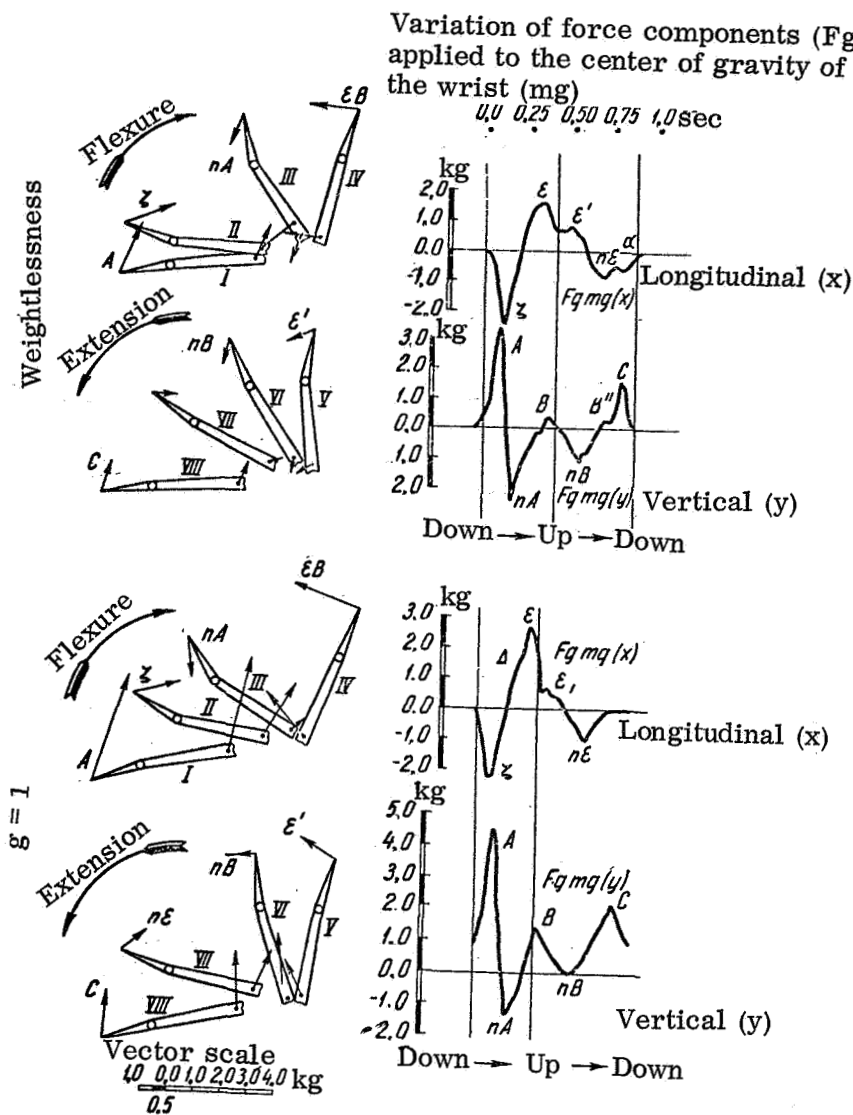


Figure 4. Coordination Structure of Flexure and Extension of the Arm of a Human Being When Accomplished at High Speed at 1 g and During Short-Term Weightlessness (above).

This fact can in no way influence the conclusions we made, although it does somewhat complicate understanding of the mechanisms governing their origin.

In carrying out slow flexure and extension under the conditions of weightlessness (Figs. 2, 3), in addition to the decrease in magnitude of the force components, also deserving of attention is the complete absence of B waves in the vertical force components, as well as the omission of the reactive B' wave and of the secondary waves A and $n\gamma$.

The reason for the absence of the B wave is that under these conditions a human being does not need to overcome the force of gravity and therefore all

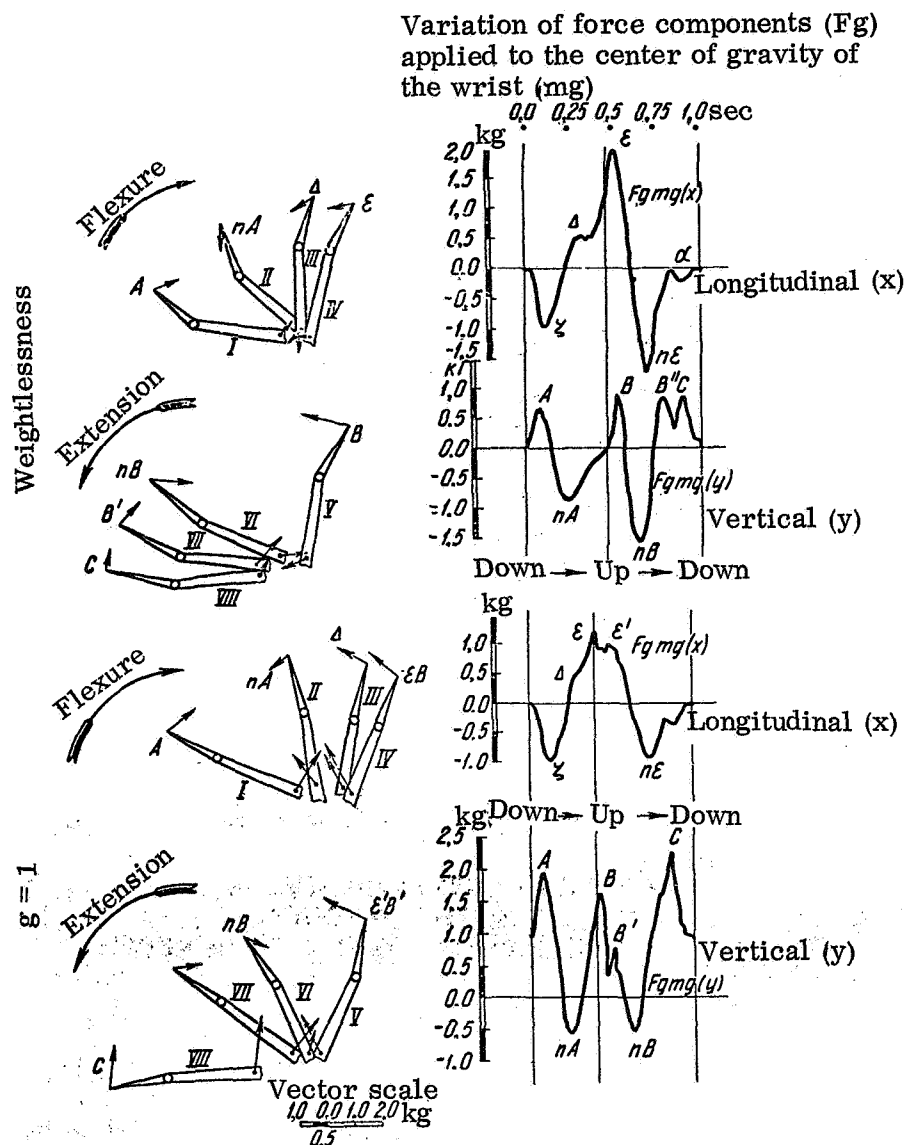


Figure 5. Coordination Structure of Rapid Flexure and Purposeful Extension (touching with the finger) of the Arm of a Man, Carried out at 1 g and Under Short-Term Weightlessness (above).

the forces of extension can be directed forward only. This is very typical for the given case and indicates not only that the reorganization of the structure of motion is correct, but also that the investigative technique we used is realistic. The very deep-seated generation of the satellite ϵ' wave is a clear indication that under the unusual conditions of weightlessness, the human central nervous system introduces additional corrections during habitual action by means of an inner loop for the control of motion. The same can also be said of the second flexural waves A' and $n\gamma$. A noticeable increase in the value of the reactive wave B' indicates a certain lack of coordination of motion. The central nervous system was not able

to eliminate this factor, which it should for sufficiently well-coordinated habitual action [1, 6].

All this leads to a certain reorganization of the force vectors applied to the center of gravity of the wrist and forearm. They are somewhat reduced and change direction from positive to decelerating, with a noticeable lag (e.g., in position IV, and not III, if compared with the upper and lower parts; Fig. 2), since minimum inertia of the body members permits simplification of the deceleration process.

If we make a comparative estimate of how large the most important dynamic and kinematic characteristics of the components of slow flexure and extension of a free arm are under the conditions of the earth's gravity field and of weightlessness, we can see considerable differences (see the table).

Deserving of particular attention is the sharp decrease in magnitude of the force vectors in the case of weightlessness, but the decrease is not the same for the various components. The vertical ones decrease by about 75 to 80%, while the longitudinal ones decrease by 30-40%. The result is an overall reduction of 50% in muscular force expended. The reason for the greater decrease of the vertical components, as compared with the longitudinal ones, is that they are affected by the gravity field. Bernshteyn has demonstrated that when the earth's gravity field acts on the vertical components of motion, these components reflect primarily the external mechanical aspect of this act - counteraction of the force of gravity, etc. This is not true in the case of weightlessness, as is evident in the greater decrease in magnitude of the vertical components and is indicative of a transfer of the dominant role in the structure of habitual action from the vertical to the longitudinal components.

Slow flexure and extension of the loaded arm in weightlessness differs from the unloaded arm case not only in the absolute magnitude of the forces applied to parts of the arm (upper part of Fig. 3), but also in that when these actions are carried out, all the above-described changes appear to be more sharply delineated. In particular, this refers to the more clearly delineated correction (satellite) wave ϵ' and to the stronger increase in value of the longitudinal components in the structure of habitual motion. The latter is evident even from the fact that the most important spontaneous - enervational wave ϵ increases by a factor of almost 2. More complex conditions of motion (a load five times heavier than the wrist itself) required reorganization of the structure of habitual motion, in fact, exactly in that direction which is almost effective under conditions of weightlessness.

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In summarizing the comparative analysis of slow motions under the conditions of weightlessness, it must be considered a fact that when man carries out similar habitual motions in dynamic weightlessness, we should expect a 50% reduction in muscular force, an increase in the part played by the longitudinal force components (which should lead to a certain reorganization of the structure of motion) and more frequent intervention of the central nervous system in the process of executing motions.

The basic feature of execution of purposeful extension under the effect of 1 g was considered to be the appearance, in the curves of the force components,

Difference in Magnitude of the Most Important Components of the Structure of Slow Flexure and Extension of a Loaded Arm When These Actions are Performed by the Same Test Subject Under Various Gravity Conditions (with respect to the center of gravity of the wrist)

Components	Normal gravity field	With a 2 g load	Weightlessness
Dynamic characteristics at the maximum (in kg)			
Longitudinal forces at the start of flexure ($n\gamma$)	0.4	0.2	0.4
Decelerating forces at the end of flexure (Δ)	0.3	0.2	0.2
Forces at the start of extension (ϵ) vertical	0.9	0.3	0.6
Forces at the start of flexure (A)	1.3	2.4	0.3
Forces at the start of extension (B)	1.3	2.2	0.0
Reactive forces of extension (B'')	0.5	2.2	0.2
Decelerating forces at the end of motion (C)	1.1	2.4	0.4
Kinematic characteristics at the extremum (in m/sec)			
Longitudinal velocity components	2.3	1.2	2.0
Vertical velocity components	2.1	1.0	1.6

of two important satellite correction waves, ϵ and B, at the start of extension.

Under conditions of weightlessness, both these satellite waves are absent (upper part of Fig. 6). Considering that the given extension was carried out within the same time interval as in the case of 1g, it can be assumed that under the conditions of weightlessness, the same purposeful form of rapid motion may be easier.

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In conclusion let us consider the execution of the above-described motions when loads of 1.8 to 2.2 g are applied (Fig. 6).

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The external conditions under which such habitual motions are executed are severe in this case, resulting in appropriate reorganization of the structure of the motions. In the execution of slow motions, the parameters of the force vectors applied to the center of gravity of the parts of the arm increase distinctly, and the magnitude of the vertical components is more than doubled (see table). At the same time the longitudinal force components even decrease somewhat. This is confirmation of the idea stated above that the dominant part played in the structure of motion in the case of weightlessness passes to the longitudinal components. Therefore, under g-loads, the opposite to what is observed in reality should occur. This is manifest in the change in direction of the total force vectors. They are directed primarily upward, facilitating successful counteraction of the increased gravity of the parts of the arm.

In the curve configuration (upper part of Fig. 6) it should be noted that the curves are extremely broken up. Since this is incident to the introduction of correction signals, it must be assumed that the unusual conditions under which this habitual motion was carried out required more frequent intervention of the central nervous system in the course of execution.

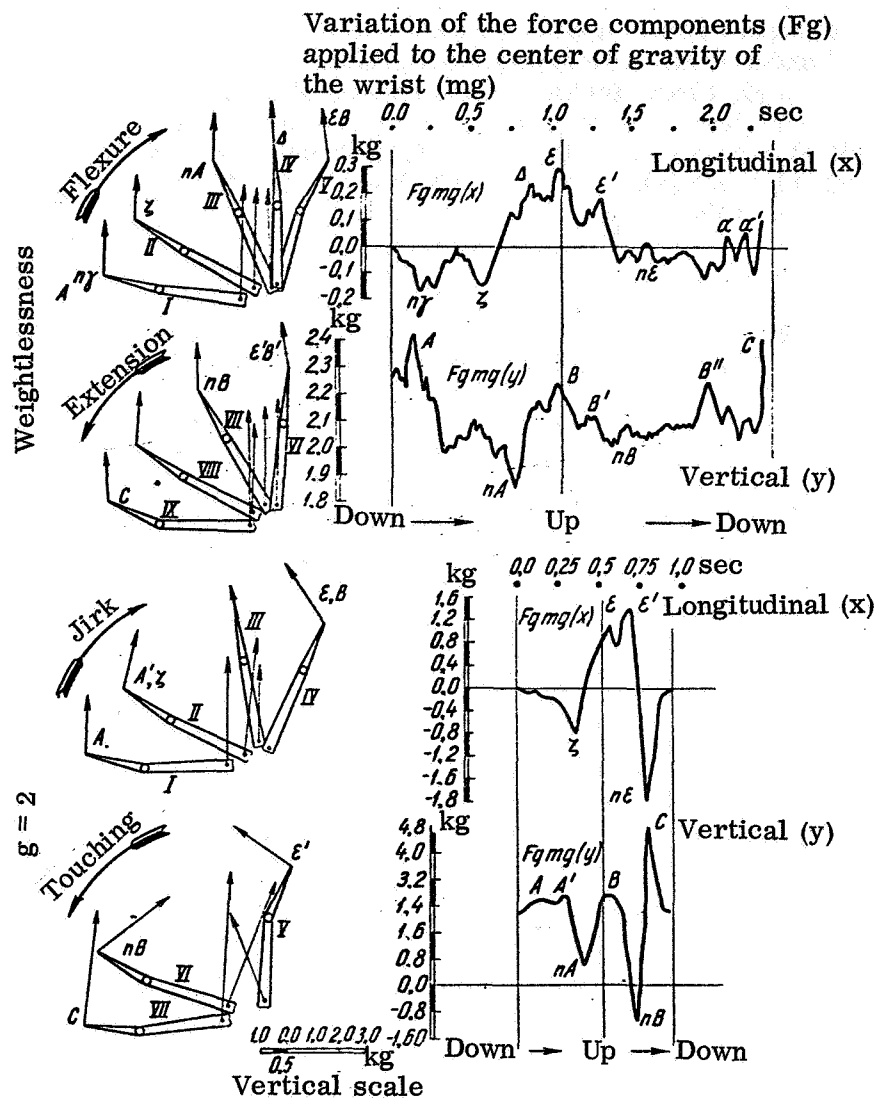


Figure 6. Coordination Structure of Slow Flexure (above) and Purposeful Extension of an Unloaded Arm of a Man Under a Force of 2 g.

When loads are applied, fast motions (e.g., flexure and purposeful extension) are carried out under a force greater than 1g, and they merge more than in the case of weightlessness. The curves of the force components have very few breaks until the end of flexure (lower part of Fig. 6). At the very beginning of such difficult extension, however, a very distinct satellite wave ϵ' is traced. It even exceeds the basic wave in magnitude. If we consider that it is absent in the case of weightlessness (it is observed only under 1 g), it must be assumed that our ideas that control of directed motions is possibly facilitated in a zero gravity field are confirmed to a significant degree.

The total force vectors applied to the parts of the arm, when fast motions are executed under loads, are appreciably greater than when these motions are executed under 1 g). Characteristic is their steep slope to the horizontal, steeper than when slow motions are executed, since quick jerking motion requires that the longitudinal components be greater. This changes the direction of the vectors, in particular of those vectors which characterize the forces applied to the center of gravity of the wrist.

On the whole, it must be pointed out that analysis of the execution of the motions we investigated, under load conditions, not only confirmed the validity of a number of conclusions obtained in considering their execution in the case of weightlessness, but also demonstrated that it is expedient to use our methods.

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THE STATE AND EFFICIENCY OF A HUMAN BEING DURING PROLONGED CONFINEMENT IN A SPACECRAFT SIMULATOR

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D.G. Maksimov, V.F. Onishchenko, and V.A. Popov

One of the factors incident to prolonged confinement of a human being in a spacecraft is the limitation of his mobility (hypodynamic). It has been shown that prolonged hypodynamia may have a deleterious effect on the functional state of the organism and efficiency of a human being [6, 7, 9, 14—16].

The problem of the present research is to study the overall state and efficiency of man during prolonged (12-day) confinement in a spacecraft simulator in the absence of special means to counteract the negative effects of hypodynamic.

METHOD

The test subject remained for 12 days in his space suit half-lying in the seat of the spacecraft simulator. The model was hermetically and acoustically sealed off from the surroundings. The microclimate in the cabin was maintained by an autonomous system in conformity with a prescribed program. The air temperature within the cabin fluctuated between 12–24°, the humidity from 45 to 65%, the oxygen content from 18 to 20%, and the carbon dioxide content did not exceed 1%. The microclimate in the pressure suit was regulated by the test subject by changing the volume of circulating air. The test subject was fed and supplied with water by using one of the various types of space rations. A special sanitation device was used to take care of the natural functions.

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For the purpose of better imitation of flight conditions, illustrations of the celestial canopy and also images of the earth and moon were set up in front of the space-cabin illuminators. According to the experimental program, at certain fixed periods the test subject oriented the craft, made a radio report, performed various test functions and made records in the spacecraft log.

The overall state and physiological reactions of the test subject were continuously monitored over a television hookup by observing the pulse rate, the respiration rate, the electrocardiogram pattern, encephalograms and other physiological indicators. A block diagram of the setup and equipment designed to monitor the state of the test subject is given in Fig. 1.

To accomplish the research goal a large complex of psychological methods was used in the experiment, and with these methods we studied such aspects as the operational reliability of the tester in controlling a spacecraft manual orientation system, the stability of complex sensomotor habits, and mental and physical capabilities. The transmission capacity of the visual analyzer was studied by the method described by A.A. Genkin, V.I. Medvedev, and M.P. Shek [2]. Tables

were compiled from Landolt rings of equally probably directions. The test subject was to look over all signs and pick out prescribed useful signals. The criteria for work evaluation were the time expended in examining tables, and also the number of recognized and transmitted useful signals. The bioelectrical activity of the muscles during tests on the coordinograph and dynamograph were determined from the wrist flexors. The galvanic skin reaction was investigated by Tarkhanou's method. The bioelectric activity of the cerebral cortex was recorded with an electroencephalograph using a frequency analyzer and frequency integrators, applied to the forehead and occiput (left side).

Before and after the experiment the test subject was given a general clinical examination, applying the orthostatic test, and was examined while applying a functional load on a treadmill and in a centrifuge. The effect of gravitational loads during rotation of the centrifuge reached 10.5 t, in a line through the chest and back. In the centrifuge experiment we studied the response reactions of the test subject to light signals and also the parameters of the medical check (EKG, KGR, the respiration rate, etc.).

EXPERIMENTAL RESULTS AND DISCUSSION

The overall state and health of the test subject during the entire experiment was satisfactory. All instructions transmitted from the monitor central were carried out in accordance with the program. Evaluation of the environmental situation and responses to questions were correct.

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In the course of the experiment the test subject development symptoms of general asthenia, accompanied by the appearances of irritability, fatigue, deteriorating appetite, a drop in the functional activity of a number of physiological systems of the organism, and some deterioration of the quality with which functional tests and special tasks included in the experimental program were performed.

The data on control of a manual spacecraft orientation system indicate that the operational reliability of a test subject underwent a number of changes. In the first three days, a tendency was noted to increase the time spent in spacecraft orientation, as compared with the original state. The work motions in control were somewhat slowed down. Following the period the time spent in orientation speeded up and did not differ appreciably from the original.

The precision with which the orientation tasks were carried out also decreased on several days of the experiment (7th and 11th).

In studying the capability of the test subject to transmit information by means of a teletype instrument it was found that the operational reliability also decreased toward the end of the experiment. The time spent to transmit a symbol increased from 0.7 to 0.8 sec. The number of transmitted symbols decreased from 1.3 to 1.2 per sec. The overall capacity insofar as time spent in transmitting standard information is concerned decreased by 10%. In order to establish the initial indexes for working habits, two exercises were required on the second day after the experiment. Each exercise included the transmission of standard tests consisting of 150 printed symbols.

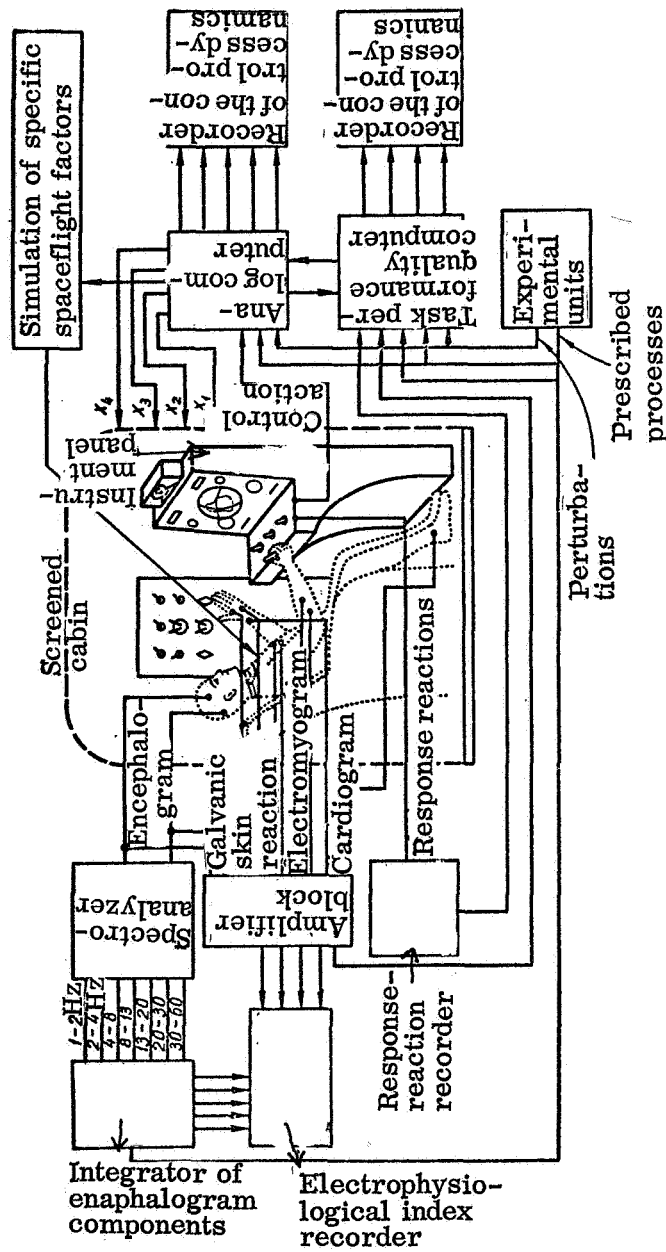


Figure 1. Block Diagram of the Recording of Certain Indicators of the State and Efficiency of the Test Subject During the Experiment.

Investigations by means of correctional tables showed that the transmission capacity of a visual analyzer in carrying out a test with Landolt rings decreased toward the end of the experiment from 1.7 to 1.3-1.5 bits/sec. Losses of useful information by the visual analyzer increased by 8-10 signals, and the time spent in recognizing useful signals increased by 30 to 60 sec. Deserving of attention is the fact that a decrease in the contrast sensitivity of the eyes to red and green light by 35 and 45%, resp., was noted toward the end of the experiment (L. N. Meier).

In analyzing the electroencephalogram records (EEG) it was found that a state of stagnant exaltation of the α -rhythm exists at the end of the experiment (Figs. 2,3). The specific intensity of this rhythm, as determined in functional tests of eye closure, increased by 16-22%. In addition to changes in the α -rhythm indexes, the EEG also revealed a tendency toward an increase in the activity of the low-frequency rhythms with an oscillation period of 2-7 Hz/sec.

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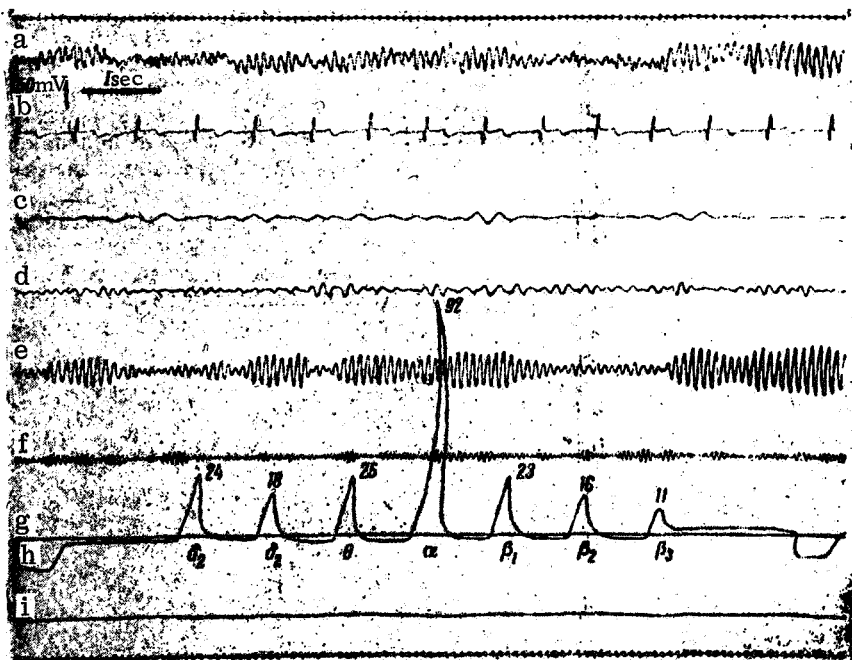


Figure 2. Sample of an EEG Record made of the Test Subject at the Beginning of the Experiment While Making a Functional Test of the Eye-Closing Operation:

a—EEG of the Forehead - Occiput, Left Side; b—EKG; c, d, e, f—Oscillation Frequencies of EEG Waves in the Range of 2-4 Hz (Δ one rhythm), 5-7 Hz θ -rhythm), 8-13 Hz (α -rhythm), 14-20 Hz β -one rhythm), as Elicited by Filters of the Analyzer; g—Amplitudes of the EEG Frequencies from Integrator Indexes over 10 sec of Analysis; h—GSR; i—EMG.

Electromyographic studies made during the execution of the functional tests indicate that the bioelectric activity of the muscles decreased appreciably toward the end of the experiment. Thus, in making a functional test of rhythmic depression of the keys of an instrument, the bioelectric activity of the flexors of the right wrist decreased from 300 to 200 microvolts. In a number of cases partial and arrhythmical oscillations were noted on the recorder EMG toward the end of the experiment.

In investigating the galvanic skin reactions (GSR) recorded while carrying out tests of the rapid transfer of attention it was observed that toward the end of the experiment the GSR amplitude dropped from 650 to 480 microvolts, i. e., by 26%.

Under the effect of the experimental conditions the test subject also showed a decrease in the functions of respiration and gas exchange. The rate of the respiratory cycles decreased from 14-13 to 10 per min during the morning hours. The greatest decrease in respiratory rate was observed on the 8th and 10th days. Toward the end of the experiment the respiratory rate increased toward the end of the experiment, reached the original values and, on the 13th day, after the cabin was unsealed, had exceeded the original values (Fig. 4). During the evening hours the respiration rate was in the range of 12-16 per min; in the second half of the experiment, a certain increase in fluctuation of the breathing rate was observed.

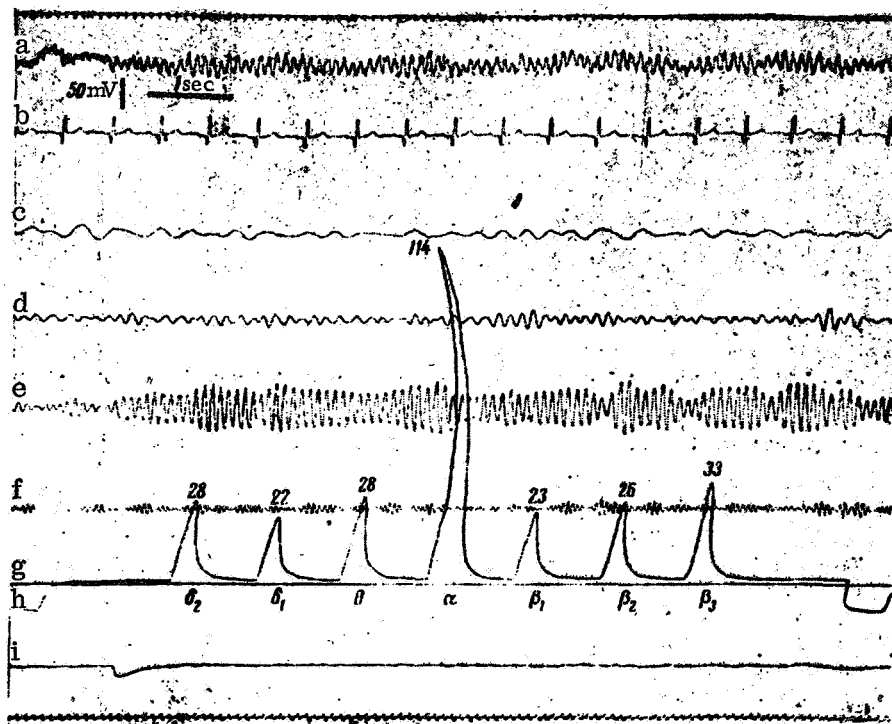


Figure 3. Sample of an EEG Record made of the Test Subject at the End of the Experiment Devoted to Testing Eye Closure.

Notation as in Fig. 2.

It should be noted that in addition to a decrease in the respiration rate of the test subject in the course of the experiment, the pulmonary ventilation also decreased by 360-1600 ml/min. The vital capacity of the lungs changed only slightly. The magnitude of the oxygen required dropped regularly from 256 to 176-240 ml/min. The dynamics of CO_2 evacuation from the human organism was 199.7 ml/min. In the next three days it had dropped to 144-147 ml/min; subsequently the amount of evacuated CO_2 fluctuated within the limits 128-202 ml/min.

The magnitude of the basic exchange in the first few days of the experiment was 1,759.7 kcal, which was 118% the required magnitude; on the 3rd and 5th days it was 1,271.5 kcal (85.3%). In the second half of the experiment the magnitude of the basic exchange again rose, lying within the range 1,551-1,681 kcal (105-114%).

In the morning hours of the first half of the experiment the pulse rate was somewhat high, as compared with the initial values, lying in the range 68-74; on the 12th day it rose temporarily to 80 per min. During the evening hours throughout the experiment a tendency was observed toward a decrease in the pulse rate from 85 to 62 per min; only on the 13th day after the cabin was opened (but the test subject was still in his seat) did the pulse rate rise to 89 per min (Fig. 4).

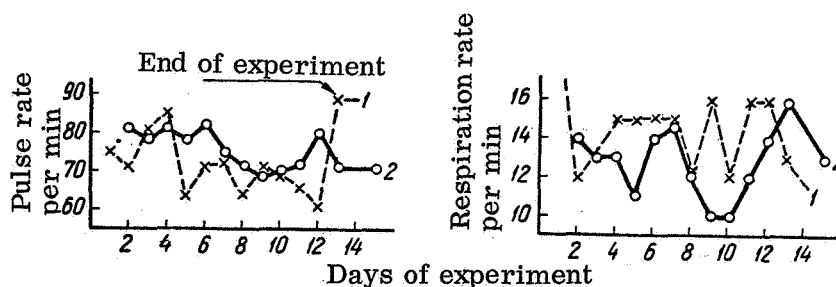


Figure 4. Dynamics of Pulse Rate and Respiration Rate of Tester on Different Days of Experiment; Evening (1) and Morning (2).

Of interest are the data on the change in pulse rate under a constant physical load while working with the wrist dynamograph. In the first half of the experiment the pulse rate during rhythmic work on the dynamograph was 115-120% of the original value, and 117-141% during the second half of the experiment. When the dynamograph was kept in the compressed state (static work), the pulse rate in the first half of the experiment increased to 112-118, and to 113-131% in the second half. When the breath was held during inspiration, the pulse rate also increased appreciably in the second half of the experiment.

Analysis of electroplethysmograms showed that the phase relations of the cardiac activity during the experiment did not exceed the mean values typical of healthy people. Only in the middle of the experiment was it possible to note some reduction in the phase of the isometric tension. Obviously such a change is characteristic of a state of hypodynamia.

Analysis of the EKG records showed a decrease in the amplitude of the R and T spurs, an insignificant decrease in the segment ST and a certain retardation of the auriculoventral conductivity. It can be assumed that the decrease in amplitude of the R and T spurs was caused not only by a change in the biomechanism of the cardiac muscle, but also by an increase of the interelectrode resistance.

With the aim of studying the hemodynamics before and after the experiment we recorded the tachoscollograms and arterial oscillograms of the test subject on a Savitsky mechanocardiograph. In a passive orthostatic check made during the first hour after the experiment, the arterial pressure of the test subject was noted to be considerably higher than in the initial state, and the volume of blood per stroke per minute was also noted to be sharply reduced. Before the experiment, the volumes per stroke per minute during the orthostatic check decreased from 89 (6.04 l/min) to 54 ml (511 l/min), while the arterial pressure increased from 112/65 to 127/78 mm Hg, but after the experiment the blood volume per stroke per minute decreased during the same functional check from 72 ml (5.13 l/min) to 44 ml (3.67 l/min), while the arterial pressure of the blood increased from 123/74 to 132/192 mm Hg (A. V. Beregovkin).

On the second day after the experiment a passive orthostatic check revealed no noticeable increase in the arterial pressure and no distinct decrease in blood volume per min, and on the third day there was almost complete recovery of the reaction of the cardiovascular system to the orthostatic check.

Deserving of attention are the data on the response of the test subject to functional tests in the form of applied loads and doses of physical work. These tests were performed both before and after the experiment under ordinary conditions.

The maximum residual stress after the experiment was almost unchanged (10.5 g's before and 10 g's after the experiment). The trend of the shifts in physiological reactions also was identical. No appreciable difference was noted in the change of respiration rate in both cases. The rate of heart contraction upon application of loads after the experiment was somewhat greater than in the initial state. The time required to normalize the pulse rate increased after the experiment to 4 min, while it was 1 min in the initial state. The responses time of motor reactions by the test subject to light signals increased considerably. Also noted were changes in the tonus of the minute veins and capillaries of the test subject. When extreme loads were applied, the amount and volume of hemorrhage into the integuments of the back, hips and buttocks of the test subject were considerably greater after the experiment than in the initial state (A. R. Kotovskaya).

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Considerable shifts in the reaction of the organism of the test subject were also observed when a 3-minute running test at the rate of 180 paces per min was completed after the experiment. Prior to the experiment, after a 3-minute run, the pulse rate increased from 74 to 152 beats/min, the breathing rate from 14 to 24 per min, and the systolic and diastolic pressures from 100/60 to 150/30 mm Hg. These physiological indexes recovered in 4 min. After the experiment, after the same exertion, the pulse rate increased from 74 to 172 beats/min, the breathing rate from 14 to 30-48 per min, and the arterial pressure from 108/58 to 170/20 mm Hg. The physiological indexes did not normalize in 5 min (A. V. Beregovkin).

During a test run with the dynamograph the test subject exhibited a post-experimental decrease in muscle strength of the right hand as well as an increase in the supplemental forces required to keep the dynamograph in the compressed state. No appreciable changes in the coordination of hand motion were observed from a coordinograph check on the 2nd and 3rd days after the experiment.

From the data of a large number of examinations no pathological changes whatever were detected in the organism of the test subject after the experiment. The periodic appearance of acetone bodies in the urine and also of an insignificant amount of sugar (0.2%) must obviously be considered as temporary functional dislocations. Also to be considered as temporary dislocations are variations in vascular reactions (plethysmograms), namely, a decrease in reaction to deep inspiration and cold, as well as the disappearance of reaction to oral counting and to brief delay in breathing.

As evident from the data, several changes were observed in the state and efficiency of the test subject, despite the fact that he estimated his state of health as completely satisfactory throughout the experiment. In view of the fact that the parameters of the microclimate in the spacecraft cabin did not change appreciably, and the food intake and water supply were normal, the above-mentioned variations in the reactions of the cardiovascular and respiratory systems and also of the overall status of the test subject are apparently related to the effect of prolonged hypodynamia and isolation. At the start of the experiment the effect of these factors was accompanied on the part of the test subject by an orientative reaction to the environment, which showed up as a persistent increase in the pulse rate, inaccuracy of motion in orienting the ship, midway in the experiment, the effect of these factors was accompanied by the development of adaptive-compensatory reactions, followed by an increase in general fatigue and disruptions in the state of a number of basic vital functions of the organism.

The presence of fatigue in the test subject showed up as a steady decrease in the quality of work in spacecraft orientation, deterioration of the motor skill in transmitting signals by teletype and a decrease in the capacity of the visual analyzer in choosing from tables of useful signals. The presence of fatigue and a decrease in the reactivity of the central nervous system are indicated by the galvanic skin reaction of the test subject to external stimulation and by a slowing down of the response reactions to light signals. At the same time the EEG revealed an increase in the index of low-frequency oscillations and exaltation of the α -rhythm.

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The general fatigue of the test subject was apparently also reflected by a decrease in muscular strength of the wrists, inaccuracy of the muscular forces, decrease and high irregularity of the amplitudes of the electromyograms accompanied by the simultaneous appearance of high-amplitude splashed.

During the experiment and for three days after it was over the reaction of the cardiovascular system in response to a passive orthostatic check and to physical forces was observed to be more pronounced than in the initial state. This is apparently a reflection as much as general fatigue and a change in the central nervous system as of the direct effect of hypodynamia on the blood circulation [1, 2]. The interruption of vascular tonus was manifested very distinctly as an increase in the amount of subcutaneous hemorrhage when forces were applied after the experiment.

Data analogous to ours on the effect of prolonged isolation and hypodynamia when test subjects are placed in the usual and a variable gaseous medium had also been collected earlier by other researchers [3, 4, 9, 11, 14, 16]. They pointed out that under the effect of hypodynamia and restriction of afferent signaling psychic reactions are combined, negativism appears in the execution of operational tests, the efficiency is lowered, and the functions of breathing and blood circulation decrease. Kakurin et al. [6] noted that prolonged hypodynamia sharply decreases the capability of the test subjects to transmit information (up to 25%). Izosimov and Myasnikov [5] observed that isolation of test subjects resulted in a decrease in reactivity and excitability of the cortex of the brain and that low-frequency components appear in the EEG. The pronounced effect of hypodynamia on the overall status and efficiency of human beings was also noted in the work of L. V. Korobkov [7] and B. A. Lampusov [8].

The above-mentioned functional dislocations in a test subject under the effects of prolonged isolation and hypodynamia make it urgently necessary to further study of the effect of these factors on the human organism and to seek optimal working and breathing conditions for astronauts.

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MAINTENANCE OF A GIVEN STATIC FORCE WHILE THE FORCE OF GRAVITY IS TRANSFORMED*

M. A. Cherepakhin

Previously we carried out an experimental investigation of certain indices of coordination of human motions when the human being was subjected to alternating stresses and weightlessness [1-3]. The experiments were carried out during jet aircraft flights along a weightlessness parabola; over certain segments of this parabola the g-forces reached 2-2.5 for a period of 10-12 sec and weightlessness lasted 17-23 sec. In each flight 4-8 parabolas were traversed.

During the flight the test subject was held by a safety belt in the pilot's seat facing an experimental console [2]. During the entire flight along the weightlessness parabola he was to hold onto a low-force electrodyneograph (designed by Ye. M. Yuganov, R. I. Utyamyshev and A. V. Yegorov) with a tension of 400 g. The electrodyneograph was attached to the vertical panel of the experimental console in front of the test subject at a height of 20 cm above the plane of the console. A scale covering 50 g was on the side of the electrodyneograph facing the test subject. The magnitude of the smallest graduation was 10 g. From these graduations it was determined how strongly special handles on the right and left sides of the electrodyneograph were pressed. The length of the projecting handles was 4 cm. The maximum angle of displacement of the handles was about 65°. This displacement, by means of a transmission system, actuated the disk with the superimposed "force scale" and recorded variations in the electrical potential on an oscillograph. /170

The test subject was obliged to keep the specified force constant for 10-15 sec in horizontal flight before going into the weightlessness parabola, during the g-force period before and after weightlessness, during weightlessness, and for the first 15 sec of subsequent horizontal flight. The handle of the electrodyneograph was depressed by the thumb of the right hand without support. Skin electrodes were attached to the upper side of the joint of the thumb of the working hand in order to record the bioelectric activity of the corresponding groups of muscles.

The test subjects worked according to the instruction: "On the light signal" attention! weightlessness," which was given in horizontal flight 10-15 sec before the aircraft went into the parabola, use the thumb of the right hand to press the handle of the electrodyneograph with a force of 400 g, while watching the scale of the instrument, and keep up this force during the entire parabola.

During the next parabola do the same thing with eyes closed. On the signal "attention! weightlessness" press on the handle with a force of 400 g, check this action visually, close your eyes and keep up this force until the aircraft leaves

*The experimental portion of the investigation was carried out under the supervision of Ye. M. Yuganov.

the parabola and gets into horizontal flight. Stop the operation on the signal "finished" in horizontal flight. "

Examined were 18 males, aged 18-43. Before the start of our research the majority of the test subjects had participated several times in flights along a weightlessness parabola. Among them were the cosmonauts Nikolayev, Bykovskiy, Kamarov and Belyayev. One test subject was the first to participate in flights along a parabola. None of the test subjects had had prior experience in maintaining a force on an electrodyamograph; they received only orientative instructions 15 to 30 min before take-off of the aircraft.

The experimental results showed that it was a rather easy task for all the test subjects to maintain the specified static force during periodic transformation of the force of gravity when the task was accomplished under visual control. But when visual control was excluded, the precision with which the required force was maintained depended on the degree and character of the change in weight of the test subject's body: under g-loads a tendency was observed to increase the force applied to the handle of the electrodyamograph and in weightlessness to decrease this force (Fig. 1). Over the horizontal flight sections the test subjects maintained the force with sufficient precision. This precision deteriorated each time that the magnitude of acceleration of the force of gravity deviated from 1 g. It should be especially emphasized that the force changed particularly abruptly toward the lower side during the first few seconds of transition to weightlessness. This was true of the test subject who first participated in flight along a weightlessness parabola, even with visual control (Fig. 2). As evident from the figure, it was only a very short time (5 sec) before the test subject began to carry out the experimental mission accurately. /171

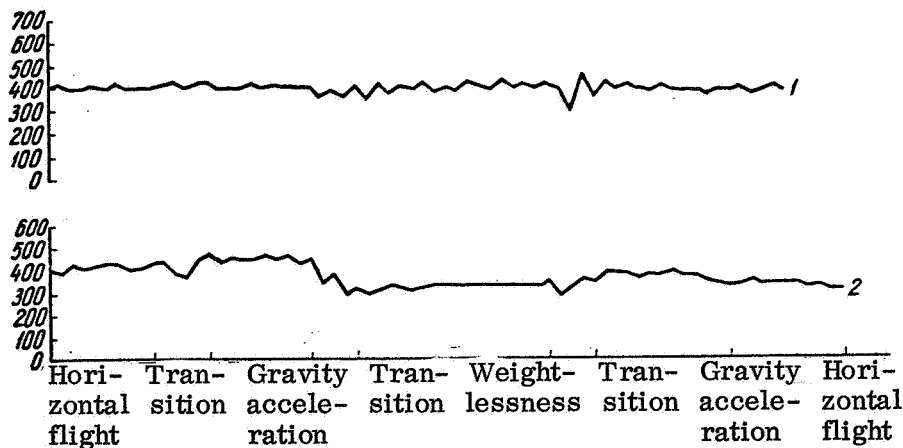


Figure 1. Graph Showing Maintenance of Force at 400 g by Test Subject With a Large Amount of Flying Experience Along Weightlessness Parabolas, With Visual Control (1) and With Eyes Closed (2).

Given in the table are the results of a statistical analysis of the data obtained when the test subjects carried out the mission with eyes closed.

From the data of the table it is evident that the magnitude of the force during weightlessness decreased as compared with the corresponding force during horizontal flight and gravity acceleration.

In horizontal flight the amplitude of oscillations of the biopotentials of the hand was minimum; it increased considerably during weightlessness (by 100-150%), but remained almost unchanged or increased only slightly in the g-force flight sections. This supports the data of our previously published work, in which the same method was used, but the test subjects who participated in it did not have experience in flying over weightlessness parabolas and did not have prior fixed experimental motor skill [1]. The amplitude of the EMG oscillations during execution of the same task, but with eyes closed, was identical in all stages of change in weightlessness, but higher by 75-100% than in horizontal flight when maintaining the force with visual control. /172

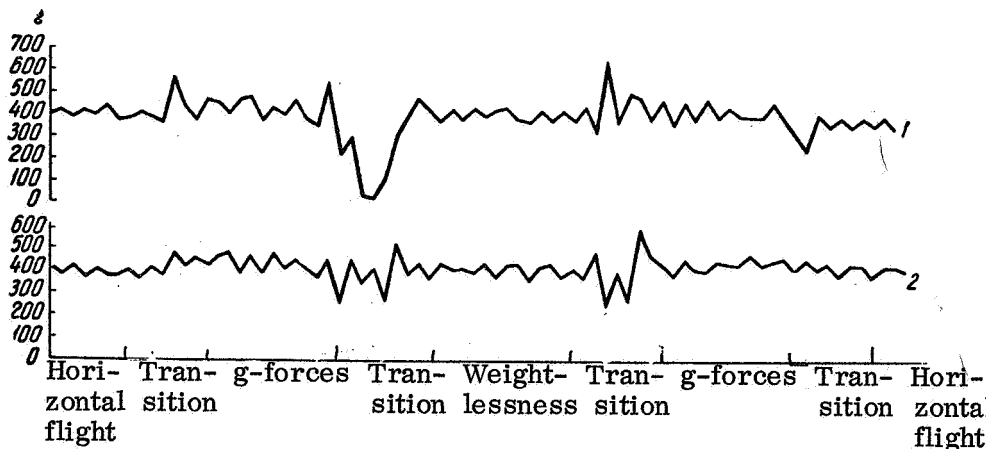


Figure 2. Graph Showing Maintenance of Force at 400 g by a Test Subject Who Was Inexperienced in Flying over Weightlessness Parabolas; With Visual Control (1) and With Eyes Closed (2).

In one series of experiments the EMG of certain posture muscles of three test subjects was recorded, in particular of the trapezius of the neck and, for comparison, of the pectoralis major.

The significance of the initial working posture for the efficiency of any motor act is well known. The posture musculature during the process of human motor activity performs specific static and dynamic work that is due primarily to the effect of the force of gravity. We assumed that under the conditions of weightlessness the bioelectric activity of the posture muscles would decrease. This working hypothesis had been confirmed earlier [1], as was true also in the present experiments. A decrease in gravity to 0 g led in all test subjects to a decrease in the bioelectric activity of the neck muscles (trapezius). The electric potential of the large pectoral muscle, taken for comparison, increased somewhat during the transition to weightlessness, but remained almost unchanged during weightlessness. /173

Maintenance of the Required Force (in g)
By Test Subjects With Eyes Closed

Statistical index	Horizontal flight (controlled)	Gravity acceleration before weightlessness	Weightlessness	Gravity acceleration after weightlessness	Horizontal flight after weightlessness and gravity acceleration
M	383	390	367	382	367
σ	62	105	83.4	95.6	104.9
m	5.6	8.00	5.0	7.5	9.6
t		0.7	2.13	1.06	1.44

Remark. M = arithmetic mean; σ = mean square deviation; m = mean error of the arithmetic mean; t = reliability factor.

Thus, a detailed analysis of mechanograms and statistical reduction of the data revealed a stable tendency toward a change in the static force as a result of transition of the test subjects to the accelerated gravity and weightlessness states and during the time these factors are effective. It was found that the magnitude of the force reflects the overall trend of the transformation of gravity. When the body weight of the test subject increased, so did the force exerted on the handle of the electrodyamograph, if the vector of gravitational acceleration coincided with the force exerted; when the weight decreased, so did the force exerted on the handle of the electrodyamograph and the body weight. When visual control is eliminated, this relationship shows up even more distinctly.

The facts we obtained contradict the data recorded in [2]. In the experiments of these authors, which were carried out under analogous conditions and by the same method, in the state of weightlessness the test subjects, trying to maintain the specified static force, pressed on the handle of the instrument with greater, and not lesser force, as in our experiments. This contradiction is of purely external character and is explained by several peculiarities of the experiments. In particular, all the test subjects were trained to maintain the force, and they advanced to the weightlessness tests only when the experimental skill had been well ingrained in them; secondly, a dosimeter was attached to the hand and could move along with the hand; and, finally, the test subjects were not experienced in flight along a weightlessness parabola. In our experiments the test personnel only received instructions and a familiarization session on how to work by the method used and were adapted to the alternating effects of gravitational acceleration and weightlessness. In other words, in our work and the cited reference, facts were obtained as to how weightlessness affects the level of the static force in trained and untrained test personnel. In the trained test subjects of [2] the acceptor of the action had been formed, whereas in our test subjects it had not yet taken shape. The presence of an action acceptor with reinforced kinesthetic components in all the test subjects caused a lapse of adequate stimulation during weightlessness, resulting in compensatory activation of the muscle groups which participated in execution of the experimental task. Thus, there was a lack of a model of the nervous stimulus, i.e., of the sensory standard which, by collating the standard with the structure and character of inverse afferentation, would have

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signaled that the task had been successfully completed. However, the mentioned phenomenon was complicated by the process of forming an action acceptor. It is completely obvious that proprioception played a part in the formation of an action acceptor, both in the familiarization session as well as in the first stages of flight, when the given force was maintained under visual control. This is testified to by the nonuniformity of the static force during transitions from gravitational acceleration to weightlessness and, conversely, from weightlessness to gravitational acceleration, as well as by the increase in the bioelectric activity of the muscles of the working hand.

There is all reason to believe that this phenomenon is caused by a change in the character of the experimental activity of the test subjects. According to the instructions, the test subjects were to maintain a given force exactly, consciously counteracting any impulse to change this force. This was comparatively easy for them in the period of horizontal flight - the corresponding curves of the mechanograms of maintenance of forces coincide sufficiently closely with a straight line. In the transitional periods the mechanograms take on the character of a broken line; the static forces of the test subjects are complicated by dynamic components. It can be assumed that this explains in a certain measure the increase in the bioelectric activity of the muscles. Moreover, in connection with the vanishing weight it is possible that it was necessary to develop additional muscular force of the hand to compensate the pressure on the handle of the electro-dynamograph, pressure which was generated during horizontal flight by the weight of the hand. In order to make this hypothesis more precise, we conducted a series of experiments with the arm fixed at the elbow and radiocarpal joints, thus preventing weight from contributing to pressure on the handle of the dynamograph. The results turned out the same as before, namely, the bioelectric potential of the muscles increased. Finally, it is incontestable that general orientative reaction to changes in weightlessness also participated in the genesis of this phenomenon. In other words, the reason for the increase in bioelectric activity of the arm muscles in our experiments is manifold.

The affect of gravitational acceleration and weightlessness as a stress factor and an external inhibitor leads to a reduction of control by the test subject of the execution of his experimental task. It was demonstrated in the work of A. S. Yegorov and Yu. Z. Zakhar'yants that in the case of identical motions, the biopotential of the respective muscles increased with a reduction in control by the test subject of the motion to be executed, forfeiting the inherent stability in the presence of control. This position of the authors is also confirmed by our observations of the maintenance of force on the electro-dynamograph with eyes closed. In this case the bioelectric activity was the same during horizontal flight, gravitational acceleration and weightlessness, but higher than when performing the same task with eyes open, whereas when performing the task with visual control the biopotential increased sharply only during weightlessness.

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In our experiments all conditions for performing the action without the usual control by the test subject when he entered the situation of alternating effects of gravitational acceleration and weightlessness were less habitual than the conditions of horizontal flight.

The above-outlined characteristics of the effect of transformation of gravity on the magnitude of static force has a pronounced individual character in test

subjects. In all the test subjects, however, we detected a stable tendency toward progressively more exact execution of the task under changing flight conditions.

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CONTRIBUTION TO THE PROBLEM OF OCULOGRAVIC ILLUSION

L. A. Kitayev-Smyk

Disturbances of the oculomotor function during weightlessness, and also during the effect of small g-forces, when hemodynamic disturbances have not yet come into the foreground, are the most noticeable subjectively. These disturbances may lead to a considerable deterioration of one operator's capability of monitoring visual reference points under such conditions, because of the creation of the illusion that they are shifting. Not accidentally, reactions of the oculomotor system were commented on in the very first papers devoted to the study of the effect of variations in weight on the human being.

On the basis of theoretical calculations a number of authors have reached the conclusion that in the transition from normal gravity to weightlessness the sensation of falling arises as well as seeming displacement in the visual field in the "downward" direction. These illusions have been called "oculogravic."

In explaining these phenomena authors have based themselves on the tonic effect of vestibular apparatuses on the eye musculature.

The significance of tonic changes of the oculomotor system in the generation of oculogravic illusions is confirmed by observations of a persistent image as gravity changes. In weightlessness the persistent image seems to be shifted upward and during gravitational acceleration downward.

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Objective proof that the eyeball rolls under such conditions was first obtained by Yuganov and his colleagues in experiments with rabbits during rocket and aircraft flights. The data they obtained permitted them to put forward the idea that the displacement of a persistent visual image, as observed by man when gravity changes, is caused by rolling of the eye as a result of the tonic vestibular effect.

A somewhat different modification of our experiments made it possible not only to determine the position of a persistent image and of a visual target during changes in weight, but also to observe their mutual displacement.

METHOD

The state of weightlessness was produced in the cabin of an aircraft flying along a parabolic trajectory. The activity of each period of weightlessness, 25-30 sec, was preceded and followed by gravitational acceleration (2 g's; 15-18 sec).

An adaptometer (ADM) was used in the investigations. Three series of experiments were carried out. In the first series the test subjects were exposed to a visual reference point (a cross) during the entire experiment. In the second series the visual reference point was presented to the test subject in horizontal

flight and was turned off 10 sec before the beginning of the first stress period, following which the test subject had to follow the resultant persistent image in total darkness throughout the experiment. In the third series the cross was illuminated in front of the test subject during horizontal flight; 10 sec before the first g-force set in it was turned off, and the test subject tracked the persistent image. In some experiments the luminous reference point was again turned on at the tenth second of weightlessness and in others at the seventh second of gravitational acceleration; the test subject was required to look at the center of the image.

The ADM adaptometer prevented the luminous pattern from moving relative to the head of the test subject; the luminous reference point was located 25 cm from the eyes. In order to evaluate the angular characteristics of the visual field, luminous reference points within the adaptometer were used: the outlines of the cross (located at five angular degrees from the center of the cross) and a luminous point lying 12 angular degrees above the center of the cross. The brightness of the visual reference point equalled 22 apostilbs.

Four people participated in the experiments; two had no reactions whatever during weightlessness, and two had pronounced psychic reactions (a sense of fear, a falling sensation) when in the state of weightlessness for the first few times.

RESULTS

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All the test subjects observed similar phenomena during the experiments. The continuously exposed visual reference point seemed to shift downward during weightlessness and upward during gravitational acceleration. In the absence of a visual reference point the persistent image, on the contrary, shifted upward during weightlessness and downward during acceleration (Fig. 1). In those cases when the cross was illuminated during weightlessness, it was found to be located below the persistent image. But when the test subjects focused their attention on the lighted reference point, the persistent image began to fall and came into line with the illuminated cross. Two test subjects noted, in addition, that they had the feeling "as if the persistent image caught up with the visual reference point, while the latter slipped away downward." The opposite phenomena were noted during gravitational acceleration: when turned on the cross proved to be above the persistent image, and the persistent image began to rise and come into line with the illuminated cross. Both the test subjects who had sensations of fear and falling during their first exposures to weightlessness reported that the distance between the centers of the persistent image and the illuminated cross was somewhat greater than 12° ; in the opinion of the others it did not exceed 5° .

Besides the above-mentioned phenomena, one test subject noted that at the instant of transition from acceleration to weightlessness, the visual reference point, when it was continuously presented throughout the experiment, "leaped upward, and only then moved downward."

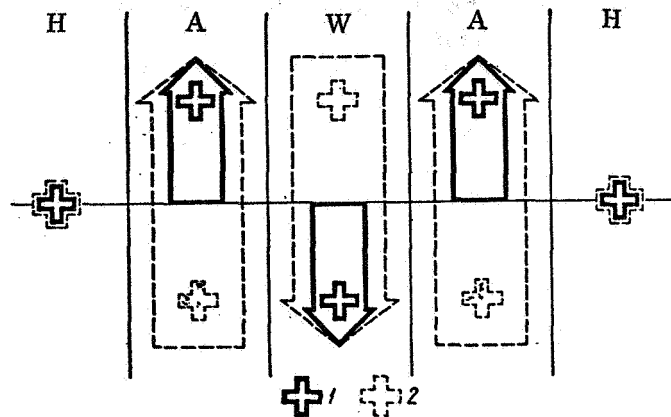


Figure 1. Diagram of the Shift of the Visual Reference Point (1) and of the Persistent Image (2) During Weightlessness (W), Acceleration (A) and Horizontal Flight (H) With Natural Gravity.

The Solid Line Represents the Position of the Reference Point and the Broken Line that of the Image; the Arrow Indicates Shift of the Image (or reference point).

DISCUSSION

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On the basis of the cited work it is possible to say with confidence that in weightlessness the forward pole of the eye shifts "upward" in man and animals and shifts "downward" in the case of gravitational acceleration, as a result of tonic reaction from the gravireceptors on the oculomotor musculature. Apparent shifts of a persistent image occur when the eyeball rolls. Up to the present time, however, no specific conclusions whatever have been drawn as to nature of the illusory motion of the visual reference points "downward during weightlessness and upward during acceleration, i. e., as to oculogravic illusion. The opinion that it may be caused by displacement of the eyeball as a result of the above-described tonic reaction does not withstand criticism, since in such a case the point of optical focus would have shifted and the visual reference point would have displaced from the center of the field of vision, which is not observed in reality. In the discussion of these phenomena in Graybill's papers, no more was said than that the aculogravic illusion is not connected with the phenomena of nystagmus.

On the basis of the results of our investigations as well as of analyzing the work of other authors, the mechanism of these illusions may be represented as follows. According to the reports of the test subjects, the illuminated reference point, when turned on during weightlessness, proves to be located below the persistent image. Efforts to focus attention on the reference point caused the persistent image to drop until it coincided with the visual reference point. This indicates that the forward pole of the eye, shifted upwards as a result of the tonic effect of gravireceptors during weightlessness, drops as a result of volitional effort, i. e., efferent cortical signals. Downward rolling of the eyeball by the

forward pole is governed, apparently, by the additional force of the inferior rectus of the eye. Simultaneously with this action the visible object seemed, according to the reports of the test subjects, to be displaced downward "slipping away from the persistent image," i.e., the optically perceived space in front of the test subjects moved downward. This, of course, could not have been caused by motion of the visual image over the retina; in our opinion, it is incident to the "displacement" of the cortical image of the optically perceived ambient space, the reasons for which may be, first, the effect of inverse afferentation from the proprioceptors of the inferior rectus of the eye, reflecting its supplementary force, and second, the direct effect of afferentation, change under the conditions of weightlessness, from the gravireceptors on the optical centers of the cortex.

Evidence for the direct effect of information from the gravireceptors, changed during weightlessness, on the higher nervous centers is provided by the fact that the action of this information causes not only apparent uniform dislocation of the visual reference points, but also, as demonstrated by our experiments, illusory distortion of their shape. The distortion occurs because elements of the visual pattern upon which attention is focused remain fixed while the elements located to the side of the focus point shift. This phenomenon cannot be explained only as a result of a change in inverse afferentation from the oculomotor system or as a result of nystagmus; without doubt it is a result of disturbance of the central integrative functions of vision. It must be noted that vertical nystagmus may occur in man because of the effect of the cancellation of gravity and may play a certain part in the genesis of optical illusions. Evidence of the presence of nystagmus during weightlessness is provided by the reports of the test subjects that visual objects "flicker" during weightlessness, and also by the nystagmoid vibration of the eyeballs during weightlessness which we observed in individual test subjects.

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Testifying to the significance of the central nervous system in organizing optical illusions is the fact that in our investigations as well as in those of other authors the oculogravic illusions were subjectively noticeable only in darkness, and in this case damping develops in the cortex of the cerebral hemispheres, i.e., its regulating function is weakened.

The character of the eyeball motion which compensates the gravireceptor tonic reaction depends on the shape of the visual reference point, in particular, on the presence of a focal point in the field of vision. A proof of this are the interesting facts obtained by Yuganov and others in flights in which short-term weightlessness was produced (28-30 sec). A tendency was observed to shift the center of the pupil upward in the case of g-loading and in the opposite sense to the level of horizontal flight or even lower in the case of weightlessness.

In our opinion these data indicate that the compensatory force of the inferior eye muscles counteracting the gravireceptor tonic reaction may be superfluous. Such "overregulation" occurred because the visible reference point was not fixed in view at the time of its illusory displacement of the ambient space during a change in gravity.

The intensity of the oculogravic illusions depended to a significant degree on the individual peculiarities of the test subjects. According to our data they were more pronounced in people who experienced a strong sense of fear and falling in their first acquaintance with weightlessness. In comparing Yuganov's data with

the results of our examination, during weightlessness, of the test subjects who participated in his tests, it was found that strong dislocations of the pupil during a change in gravity occurred in people who had more pronounced psychic reactions on the occasion of their first exposure to weightlessness.

Without examining in greater detail in this section the mechanisms by which vision is disturbed during changes in gravity, let us recall the work of Shone who, on the basis of his investigations using a centrifuge, asserts that the magnitude of vertical displacement in the case of oculogravic illusion does not depend on the pressure exerted by the otolith organs of the utriculi on maculae. According to his data, the magnitude of the displacement is found to be in correlational agreement with the degree of slope of the tiny sensitive hairs of the otoliths. /180

Thus, the data of the present investigation, as well as the studies of other authors, make it possible to assume that oculogravic illusion in weightlessness occurs under the effect of inverse afferentation, signaling changes in the oculomotor system, the changes compensating the tonic effect of gravireceptors on the system. During weightlessness an oculomotor reaction (with a downward displacement of the pupils) is possible which is opposite to the reaction from the gravireceptors that arises under such conditions; the motion of the eyes, with downward displacement of the pupils, is a consequence of excessive compensation of the gravireceptor tonic reaction. More pronounced oculogravic illusions occur in people who have a tendency to psychic reactions under these conditions (sense of falling, of fear).

OPTICAL ILLUSIONS IN MAN IN THE CASE OF WEIGHT- LESSNESS AND OF THE COMBINED EFFECTS OF WEIGHTLESSNESS, ANGULAR AND CORIOLIS ACCELERATION

L. A. Kitayev-Smyk

During space flights the character of spatial perception, including optical perception, will be affected not only by changes in linear acceleration, weightlessness, but also by angular and coriolis acceleration against a background of changed gravitation, in which it is found that angular and coriolis acceleration lower the quality of work by a human operator during weightlessness to a greater degree than does normal gravity.

Given in the present report are the results of research into human perception of plane figures in the case of weightlessness and under the combined action of weightlessness, angular and coriolis acceleration.

METHOD

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The state of weightlessness was produced in the cabin of an aircraft flying along a parabolic trajectory.

During horizontal flight with natural gravity, during g-loading and weightlessness the test subjects were presented (one each) the patterns shown in Fig. 1. The angular size of each pattern was 7° , while that of the point was 28 min. The experiments were performed in darkness; the patterns were illuminated and were placed at a distance of 100 cm from the eyes of the test subject. During daylight black figures centered on a 30 cm square were presented at a distance of 50 cm from the test subject. The head of the test subject was held vertical with respect to the aircraft. The figures were presented at eye level. The test subjects were able to note the duration of illusory perception by pressing a button, which was registered by an automatic recorder. After each experiment the test subjects gave a detailed account of the observed changes in shape and the displacements of the figure, or individual parts of it. After the flight they prepared a written account, if possible illustrating it with sketches of the changes in the visual objects noted at the respective times.

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Participants in the experiments were 28 persons, 20 in the experiment in darkness and 17 during daylight. Each test subject participated in experiments of 6-30 weightlessness periods.

The combined-action experiments, with the test subject exposed to weightlessness, angular and coriolis acceleration, were carried out with 6 men in whom stable optical illusions were observed in preliminary experiments.

Test subject						
Z-v	a	Without change				
	b	Without change				
E-v	a	Dif-fused				
	b	Dif-fused				
Zh-v	a	In the first 5sec the sharpness of the images is lost Everything pales				
	b	Becomes brighter				
Bu-v	a	The entire image moves upward then downward				
	b	Without change				
Bo-v	a,b	The entire image grows				
T-n	a,b	Appearance of a broad violet halo around the illuminated image				

◦ fixed attention

Figure 1. Examples of Optical Illusions Occurring During Weightlessness When Considered Casually (a) and When Considered With a Fixed Stare and Concentrated Attention (b).

The angular and coriolis accelerations were produced by means of a rotating seat, containing the test subject, installed in a darkened portion of an aircraft. A screen fixed to the seat was set up vertically in front of the test subject; on the screen was presented an illuminated image of one of the figures shown in Fig. 1. The effect of angular acceleration was created when the continuously rotating seat was stopped; coriolis acceleration occurred when the test subjects lifted their heads, which had been bent forward, during uniform rotation. In all tests the speed of rotation was 30 rpm. The test subjects lifted their heads for about 0.5 sec; the time of slowdown to stoppage of the seat was 0.5 sec.

Linear acceleration was produced when the test subjects moved "vertically" upward or downward during weightlessness. This created a state of partial weightlessness, positive or negative, equal to approximately 1 g and lasting about 1 sec. Each test subject was subjected to 6-10 experiments.

RESULTS

Of the 28 people who participated in the experiments, 19 noted a change in the observed objects during weightlessness. The reports of these people were rather varied, but from among the various illusory phenomena it is possible to single out individual characteristic types of illusions: 1) an increase in the size of the entire figure; 2) illusory motion of the entire figure; 3) distortion of the figure as a result of an increase of motion of its individual parts; 4) a change in the color intensity of the entire figure or parts of it; 5) the appearance of a violet halo around the illuminated figure.

As reported by the test subjects, the illusions occurred with the onset of weightlessness. The various types of illusions were of differing duration. According to the button-pressing records, the illusions appeared either during the period of decreasing weight or during the first second of weightlessness. In the experiments in which weightlessness was produced immediately after the natural gravity state and g-loading did not precede weightlessness, the illusions were of the same nature as when weightlessness set in after g-loading, but were less sharply pronounced.

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Twelve people reported apparent increase of the figures under weightlessness. Of these 4 reported uniform increase of the figures, 5 reported increase only in the vertical direction and 3 that the figures seemed to grow in size during vertical flight, but that their horizontal dimensions seemed to decrease, i. e., the figures seemed stretched vertically and narrow. According to the accounts of 5 of the 12 test subjects, individual elements of the figures (broken lines) became somewhat thicker during weightlessness; 5 observed fluctuating expansion of the figures under the same conditions.

Illusions of the described type were rather stable and were maintained throughout the period of weightlessness; they reappeared frequently in succeeding experiments, in many flights.

Thirteen men noted that the visible object blurred, or that a "loop" or "tail," in the downward direction or on either side of the figure appeared. But this phenomenon recurred several times in only 3 men being observed over the entire period of the experiment. Similar illusory blurring of the figure was observed by the remaining 10 test subjects only in the first 3-5 sec of weightlessness, and blurring ceased to occur from the 3rd to 7th period of weightlessness.

Seven people reported that they observed a smooth downward motion of the entire figure or parts of it under weightlessness, but this did not result in disintegration of the figure. When the view was focused on a certain part of the object, this part became stable, but the other parts continued to move. It seemed to three test subjects that the visible image jumped upward abruptly during the transition from g-loading to weightlessness and from weightlessness to subsequent-loading.

Four test subjects noted a decrease in brightness of the figure with the onset of weightlessness. In the case of fixed attention and view focused, the brightness of the object, on the contrary, increased at the focal point, but at some distance from this point the brightness was reduced.

Four test subjects observed doubling of the visual image under weightlessness.

Various illusory phenomena were frequently formed in the same test subjects, and as a result apparent distortions were observed; thus, the "vertical figure" took on a sigma shape, a circle appeared to be similar to a "pear," a "square" was transformed into a "rhomb," etc.

Some test subjects remarked that an illusory decrease in the size of the visible figures occurred during g-loading; i. e., phenomena which are opposite in nature to the illusions observed in weightlessness.

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In the experiments carried out in darkness, the appearance of stable illusions was more frequent than in the daylight case.

The illusions appeared brightest at the beginning of the first period of weightlessness. Their intensity decreased on repeated exposure to weightlessness.

It is interesting to note that the above-described illusory distortion of figures was observed only by people who in their first few exposures to weightlessness experienced the illusion of falling, accompanied by a sense of fear, although the sensation of falling had ceased to appear in the majority of them by the time of the present experiments as a result of adaptation to weightlessness. More pronounced and stable illusions were found in people who, exposed to weightlessness for the first time, experienced a more intense illusion of falling and a strong sense of fear. People who had experienced other spatial illusions, e. g., upside-down position, side-eying position, upward lift, etc., did not note figure distortion in weightlessness.

Four of the people who had not observed any displacements or changes in shape of the figures during the experiments reported that during weightlessness they saw a broad violet halo form around the illuminated figure, and one test subject felt that a greenish-bluish halo formed. Illusions of this type persisted during the entire period of weightlessness, being repeated in many experiments.

The optical sensations in response to the effect of linear, angular and coriolis acceleration were similar for each form of acceleration in all 6 test subjects.

When a human being is subjected to linear, vertical acceleration, positive or negative, during weightlessness, the optical illusions disappear.

Angular and coriolis acceleration and their after effects during weightlessness, by aggravating the illusions, may cause additional distortion and motion of the observed figures.

During angular acceleration and the period of its aftereffect, the test subjects noted that the figures flickered, the entire figure expanded rhythmically, individual elements of the figure diverged to the sides and moved rhythmically (rotated, tilted), with particular intensity at the point of focus, resulting occasionally in complete disintegration of the figure; also observed was an increase in the horizontal dimensions of the figure and all its parts, motion of the figure, either smoothly or jerkily, to the side opposite to body rotation.

Typical illusions occurring under the effect of coriolis acceleration were inclination or rotation of the entire figure and chaotic motion of individual, broken-line elements of the figure, blurring of the elements, and expansion at the focal point in the case of fixed attention.

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DISCUSSION

Upward motion of visible objects with decreasing gravity, in our opinion, may be a result of lowering of the crystalline lens due to weakening of Zinn's ligament, because of intensification of the accommodation effort of the ciliary muscle.

Evidence of an increase in the accommodational capabilities is provided by our discovery, during weightlessness, of the approach of "near," and especially of "very near" points of clear vision. Symptoms of myopia were also observed in studying eye refraction in test subjects who considered objects at a distance of 8 m during weightlessness. Tension of the ciliary muscle is, probably, a result of the parasympathicotropic effect of weightlessness, which was detected both during prolonged (Gazenko, Bayevskiy) as well as short-term (Kitayev-Smyk) action.

Intensification of accommodation doubtlessly causes compensational effects. As is well known, inverse afferentation in this case informs the consciousness of signals that the visible object has either expanded or receded. In our experiments, when the aircraft cabin was perceived constantly, the test subjects perceived these signals during weightlessness as evidence of the expansion of the visible objects. When extra-cabin objects known to the observer were examined, the attenuating accommodation will lead to the illusory perception that they are moving away. The correctness of our assumption has been proved in actual space flight by MacDivitt, to whom the distance to the carrier rocket, visible through an illuminator, seemed to be 5 times greater than it was in fact.

Illusory "magnification-recession" may also be caused by additional effort toward divergence of the eyes when the angle of vision at which the object is sighted does not change. However, as demonstrated by our determination of the nearest point of binocular vision, this is not observed during short-term weightlessness. On the contrary, we observed weakening of convergence, which must be compensated for by reinforcing convergence in order to keep the angle of inclination of the optical axes constant. It is known that illusory approach or decrease in size of a visual object occurs when vestibular stimuli result in additional forces of convergence. Consequently, during weightlessness two stimuli of opposite effect operate to affect perception of the surrounding space. Intensification of accommodation and the necessity of compensating for it may lead to illusory "magnification-recession" of visual objects, while a decrease of convergence and of its compensation lead to illusory "reduction - approach" of these objects. As shown by our experiments under short-term weightlessness and the observations of MacDivitt under the prolonged effect of weightlessness, the first illusion gains the upper hand. Probably the considerable difficulties of MacDivitt in determining distance in space are explained by competition between the two influences.

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Interruption of the functions of the oculomotor system during weightlessness was reported on the basis of analysis of oculograms taken from the cosmonauts

in flight. This is also testified to by the doubling of the visible image described in the present paper.

Insofar as the mechanisms of the other illusions observed in our experiments are concerned, only assumptions can be made here too. It is possible that the appearance of the violet halo during weightlessness is a result of chromatic aberration when accommodation is intensified. The occurrence of myopia may be somewhat related to the illusions observed by several people which may be explained as variations in the peripheral sections of the optical analyzer.

The illusory distortions of figures observed in the absence of gravity are doubtlessly attendant upon changes in central mechanisms.

Various distortions of optically perceived space were described during the action of stimulating and inhibiting effects applied to various levels of the vestibular and cutaneous muscle analyzers.

According to the data of Merkulov and Zhabotinskaya, patients with affected reticular formation of the stem without ocular pathology complained of apparent scintillation, pulsation or vague fluctuating vision of objects.

When damage is incurred in the region of the posterior longitudinal fasciculus, patients are afflicted with "Pieck's illusion"; it seems to them that walls are bending out, and that people around them can pass through the walls into the next rooms (cited after Bing and Bruckner). It is believed that in such cases there is a lack of correspondence between optically and vestibularly governed perception of space as a result of attenuation or interruption of pulses from the vestibular apparatus to the nuclei of the oculomotor nerves.

Many reports are available on the occurrence of optical illusions similar to those described in the present paper when certain sectors of the cortex of the cerebral hemispheres are stimulated directly or destroyed. In this respect of special interest is the temporal-parietal region of the cortex. When it is stimulated by electric current during an operation, familiar objects seem to the patients to be frightfully distorted, approaching or receding. Hoff and Kamin reported that a patient with a skull defect in the parieto-occipital region on the left, when the skin was cooled at the defect point with ethyl chloride, observed the entire visible space to be shifted to a side opposite to the damaged side, letters appeared to be distorted and piled up one on the other.

Characteristic of people with a diseased center in the temporal lobe, the region of vestibular representation, are illusory, fantastic distortion of visible objects and their apparant plurality, as well as motion and pulsation; the distortions may be provoked by cooling the neck and the pluraity by vestibular nystagmus.

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The cited facts indicate the special part played by the temporal-parietal cortex in organizing the process of optical perception when the latter is coordinated with information arriving from the vestibular and cutaneous muscle analyzers.

In Petzl's opinion, field 39 (the inferior parietal region) is the seat of mechanisms whose significance is found to consist in suppressing superfluous

pulses coming from the various afferent systems (especially from the vestibular) into the visual sphere. When these superfluous pulses penetrate the sphere, the acuity of optical perception is disturbed. The same opinion is supported by the work of Hernandez - Peon, who used electrophysiological methods of investigation, arriving at the conclusion of the existence in the human brain of an entire system of filters which prevents hyperactivity of the sensory nervous and, thus, prevents excessive bombardment of the brain by afferent pulses.

On the basis of numerous experiments with animals, Khananashvili also confirms the fact that the "posterior section of the parietal region (field 7) in higher mammals has a definite significance in the process of interaction between different cortical analyzers. This region promotes the normal flow of nervous processes which take care of complex analysis and synthesis of optical and acoustic stimuli."

Thus, based on the cited literary data, it can be assumed that the optical illusions described in this paper, occurring in a number of people in the initial period of the effect of weightlessness, are of gravireceptor, primarily labyrinth origin and take place against a background of change of the central, possibly of the corticofugal influences regulating the influx of gravireceptor afferentation and coordinating this activity with the optical analyzer system. It does not seem possible at the present time, due to the lack of the necessary experimental data, to localize these variations, to establish how high up in the cerebral system they occur.

As a confirmation of the expressed opinion concerning the central mechanism by which the interruptions of vision described in this paper occur let us cite the fact that in the present paper as well as numerous investigations of an "oculogravic" illusion similar in origin to the phenomena described here, interruptions of optical perception took place only when the force of gravity was changed in darkness, when, as is well known, slowdown of the cortical functions is observed.

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Without going into detail in the present report on a discussion of the reasons why optical illusions were noted only by people who, making their first acquaintance with weightlessness, experienced sensations of "falling", "collapse", fear and disorientation, replaced by varying degree of euphoria, let us recall how these sensations are similar to the "end of the world" syndrome described by Shmar'yan in people whose temporal cerebral lobes have been damaged. Typical of such patients is also the feeling of "falling into an abyss", accompanied by disorientation. Euphoria, with the phenomenon of sensory disintegration, has been observed in patients having tumors of the temporal lobe with simultaneous damage to the diencephalic region.

It is also known that when people who experience sensations of falling and fear at the beginning of weightlessness are repeatedly exposed to these conditions, they have, as a rule, no vegetative disturbances, in contrast with test subjects who, during weightlessness, had no emotional reactions, optical disturbances and did not suffer from vegetative disruptions. These characteristics permit us to assume that there exist groups of people whose sensory interrelationships differ in character under such conditions.

Stabilization of the visual image at the point of focus in the case of fixed attention, as described in this paper, is understandable from the viewpoint of psychological as well as electrophysiological concepts. The reliability of the information obtained increases thanks to activation of the optical cortex and of corticofugal effects on systems which filter the excess information. Interesting is the fact that when the semicircular canals are stimulated during weightlessness, concentration of attention increases illusory dislocation and distortion at the point of focus. In the light of the clinical material presented above it must be assumed that in the latter case that the mechanisms by which excess information is filtered out cannot cope with the higher vestibular influences reaching the cortex in this case. Activation of the cortex during concentrated attention only deepens the conflict between the optical and vestibular information.

PROBLEMS INVOLVED IN THE HABITABILITY AND HYGIENE OF SPACECRAFT CABINS

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Physiological-Hygienic Evaluation of the Life-Support Systems of the "Vostok" and Voskhod" Spacecraft*

G.I. Voronin, A.M. Genin and A.G. Fomin

The physiological-hygienic requirements imposed on the life-support systems of the spacecraft Vostok and Voskhod were formulated while designing the craft and were amended in laboratory and test-stand trials. In determining the basic parameters of the artificial atmosphere and in selecting the overall arrangement of the life-support system we took into account the planned flight conditions and the possible emergency situations.

The flights of the first Vostok spacecraft were calculated for comparatively brief orbital periods, but at the same time provisions were made for using craft of the given design for longer flights. Also planned for was the possibility of an emergency situation in which the duration of the flight could be increased to 7-12 days with constant increase in air temperature and in safeguards in the cabin of up to +35°C.

Moreover, the possibility was not excluded of depressurizing the cabin in flight and of the occurrence of abrupt barometric pressure gradients in case of emergency ejection of the cosmonauts during the orbital injection phase.

In this context the air regeneration and conditioning systems and the nutrition and water-supply systems in the spacecraft were constructed on the basis of a 12-day flight supply for one cosmonaut in a sealed cabin. In the case of emergency depressurization of the cabin provisions were made to use a rescue suit during the time required to choose a favorable touchdown site and to land the spacecraft.

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In order to develop life-support systems it is necessary first of all to establish the values of the average daily as well as the minimum and maximum human energy expended under spaceflight conditions. This in turn determines the magnitude of the gas exchange and makes it possible to estimate the human nutritional requirements.

In view of the fact that at the time when the life-support system of the Vostok was constructed, no experimental data existed on the effect of the complex of spaceflight factors on human energy expenditure and gas exchange, it was necessary to use indirect data obtained by reproducing the nature and volume of the proposed cosmonauts activity under laboratory conditions, simulating confinement in a spacecraft cabin.

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For this purpose we set up 15 experiments with test subjects in pressurized cabins, simulating the activity corresponding to the various stages of the space flight. As the test subjects we selected healthy young males weighing 65-72 kg, height 166-173 cm; the duration of the experiments was from 1 to 15 days.

In seven experiments the test subjects were in a pressurized mock-up of the Vostok in suits which were ventilated by the air in the cabin with an air flow rate of 50-200 l/min; the temperature of the air and the safety devices in 10 experiments was $20 \pm 2^\circ$. In five experiments lasting 12-13 days the air temperature gradually rose to 35° . The gas exchange, energy expenditure, and moisture extraction were investigated in all the experiments on the basis of the results of an analysis of the regenerated materials and of the drying agents and in part of the experiments the study was duplicated by Douglas-Holden measurements. In addition, special experiments were conducted in which the energy expenditure of the test subjects and of the cabin equipment was determined by the direct calorimetric method.

As a result of our investigations we obtained the following data:

- average daily oxygen requirements: 480-530 l;
- average daily CO_2 liberated: 390-430 l;
- average daily moisture generated: 980-1120 l (at an air temperature of $15-22^\circ$);
- average daily heat produced: 2310-2250 kcal;
- maximum energy expended while awake: 228 kcal/hr;
- maximum energy expended while sleeping: 70 kcal/hr.

Studies of the gas exchange and energy expenditure of the cosmonauts Yu. A. Gagarin, G.S. Titov, et al., were made in mock-up of the spacecraft and yielded analogous results.

Of course, in carrying out the above-enumerated experiments, weightlessness and emotional stress of the cosmonauts attendant upon the unusual status of the first flights were not reproduced. However, these figures can be taken approximately as a basis for designing life-support systems while providing for a reserve in case of unforeseen circumstances. Moreover, the first brief spaceflights were to apply a known correction to the calculations.

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Food rations were worked out simultaneously with the experiments aimed at determining the gas exchange and the energy expenditures. Investigated were the basic biochemical indices of the metabolism of the test subjects and cosmonauts under simulated spaceflight conditions. It was found that the organism has a higher requirement of proteins and vitamins.

The food ration in the Vostok spacecraft consisted of two portions. The first was intended for the planned duration of the flight; the calorie intake was 2500-2700 kcal/day with an average protein content of 120 g/day, fat content of 85 g/day, and hydrocarbon content of 300 g/day. The second part of the ration was intended to

be used in an emergency situation, when the length of the flight might be extended. The calory intake of the emergency ration was 1450 kcal/day.

The make-up of the food ration underwent some modifications from flight to flight; the reason for the modifications was to partially replace the paste-like food preserves, which constituted the main content of the Vostok and Vostok-2 ration, by natural food products in all the subsequent spacecraft.

The water-supply system was calculated for a total water requirement (including the water contained in the food products) of 2200 g/day, which in the laboratory experiments considerably surpassed the amounts necessary to maintain the water balance of the test subjects and cosmonauts.

Regeneration systems for the air conditions of the Vostok and Voskhod spacecraft were based on the amounts of oxygen and absorbents taking up the water vapor and CO_2 of low partial pressure. A certain portion of the moisture was extracted from the air of the cabin and condensed on the surface of the heat-exchanger. The oxygen was preserved in the chemically bonded state in the form of alkali metal peroxides. The use of chemically bonded oxygen was based on the idea of achieving high system reliability at relatively favorable weight characteristics. By absorbing moisture the superoxides liberated oxygen, and the generated alkali absorbed CO_2 . Silica gel impregnated with lithium chloride and activated carbon were used as supplementary drying agents. Other gaseous products of metabolism were broken down and absorbed by the regenerative substances and by special filters.

The magnitude of ventilation through the regeneration system was calculated to maintain the CO_2 concentration at the level of 0.5-1% at a CO_2 generation rate by one cosmonaut of 20 l/hr. With due regard to the depreciation in absorbence of the material as it is used, the magnitude of ventilation was established at 50 l/min for the Vostok and 180 l/min for the Voskhod. /192

Since the air-conditioning systems of the Vostok and Voskhod differed but slightly from each other, they can be examined as to components and arrangement using the single block diagram given in Fig. 1. The system consisted of four basic functional units:

- automatic maintenance of the required gaseous composition of the air in the cabin; /193
- automatic maintenance of the prescribed air humidity in the cabin;
- automatic maintenance of the necessary temperature conditions;
- control of the basic parameters of the gas medium in the cabin.

The unit for automatically maintaining the necessary composition of the gaseous medium of the sealed cabin incorporated the following elements:

- two ventilators with electric drive;
- regenerator with regulator;
- antidust filter and noxious impurity filters.

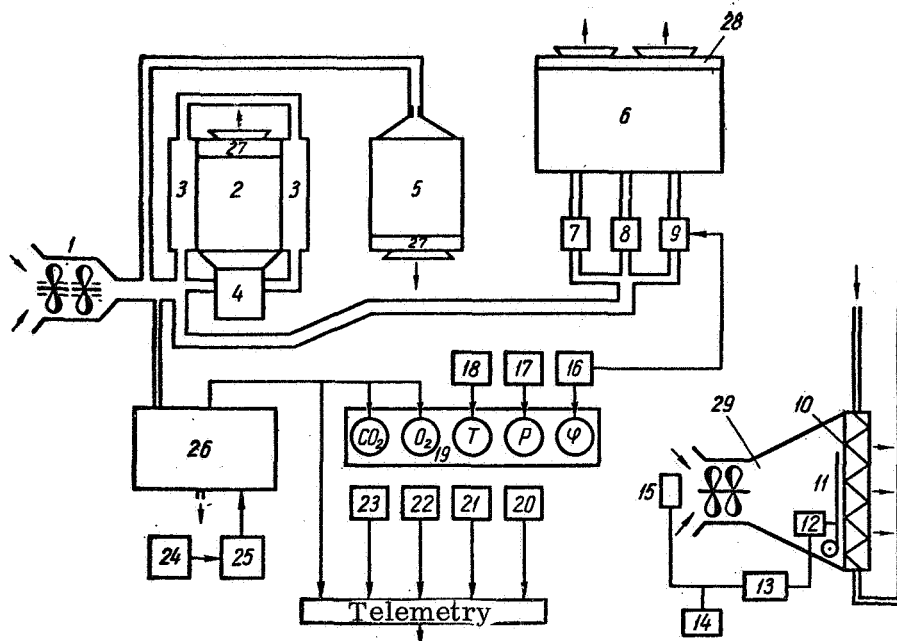


Figure 1. Block Diagram of the Regeneration and Air-Conditioning System of the Spacecraft Vostok:

1—Ventilator; 2, 3, 4—Regenerator with Regulator; 5, 6—Dehumidifier; 7, 8—Stopcocks with Manual Control; 9—Automatic Stopcock; 10—Liquid-Air Heat Exchanger; 11—Radiator Screen; 12—Effector Mechanism (screen drive); 13—Amplifier; 14—Temperature Control; 15—Temperature Gauge; 16—Humidity Indicator and Meter; 17—Pressure Meter; 18—Temperature Meter; 19—Instrument Panel; 20, 21, 22, 23—Telemetry Pickups: Pressure, Temperature, Humidity; 24, 25, 26—O₂ and CO₂ Gas Analyzers; 27—Noxious-admixture Filter; 29—Temperature Regulation Unit.

In order to ensure a continuous air flow through the regenerator, a dual, electrically driven ventilator is used in the system. The inclusion of two ventilators considerably increased the reliability of the system. In the case of failure of the main ventilator, the reserve ventilator is automatically switched in.

By means of an air collector the air flow from the ventilator is distributed through all the lines of the regeneration system.

The regenerator and the regulator were combined into a single unit. The regenerator was in the form of a metallic container holding the regeneration agent with an oxygen supply for the entire planned flight period. A filter was mounted at the outlet from the regeneration unit. The regulator, which was designed to maintain a certain oxygen concentration in the gas environment of the cabin, included a distribution valve with a sensitive element reactive to the change of partial oxygen pressure in the cabin.

Since the zone of tolerable fluctuation of the partial oxygen pressure in the inhaled air is sufficiently broad, no rigid requirements were imposed on the regulator with respect to a decrease in the amplitude of fluctuations in the oxygen concentration during regulation. This permitted substantial simplification of the regulator design and appreciable improvement in reliability of the regulator as well as of the system as a whole.

Since only a part of the moisture liberated by a human being during active work is absorbed by the operation of the regeneration unit, an additional drying unit was planned in the system to remove the excess moisture from the air. The task of this unit was automatic maintenance of the prescribed humidity of the air in the sealed cabin. The dehumidifier unit incorporated the following components:

- two capsules filled with the drying agent;
- an automatic tap;
- two manually operated taps;
- a device for collecting the condensate in the heat exchanger;
- a humidity indicator.

The first capsule was connected to the air collector of the air supply system, which had a calibrated aperture. A constant flow of air is established through the dehumidifiers, and it is actuated together with the entire system.

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The second capsule of the drying system is connected to the collector of the air regeneration system by pipes. An automatic and manual taps were installed in the air supply lines. The flow of air through the unit was regulated by an automatic indicator and manually.

The volume of the first absorptive capsule and the magnitude of air ventilated through it were designed so as to allow absorption of all the moisture liberated by a cosmonaut while resting and under comfortable temperature conditions (40-50 g/hr), minus the moisture absorbed by the regenerator.

At the same time the relative humidity level in the cabin must not exceed 70%. If the moisture liberated by the occupant increased in the case of accidental rise in cabin air temperature or for any other reason attendant upon emotional stress or active work, the air humidity increased and the second, reserve dehumidifier automatically cut in. Upon an accidental increase in air temperature, when a considerable portion of heat was released as a result of evaporation of perspiration, the cosmonaut could manually open taps, appreciably increasing ventilation through the dehumidifier. This made it possible to maintain heat balance when the air temperature increased to 35°.

The relationship between the magnitude of air ventilation through the dehumidifiers and regeneration capsules, and also the moisture capacity of all aggregates of the air regeneration system were determined on the basis of a calculation of the optimal processing mode of the regeneration agent to maintain the most favorable conditions for the cosmonauts in the case of normal and emergency situations.

The unit for automatic maintenance of the given temperature schedule consisted of two circuits: one, an air circuit opened out into the space of the sealed cabin and a liquid one, closed to heat radiation. The latter was located on the outer surface of the spacecraft.

Contact between the two circuits was established by means of a liquid-air heat exchanger located inside the cabin.

The components of the heat-regulation system which were installed inside the cabin of the spacecraft included:

- a liquid-air heat exchanger;
- electrically driven ventilator;
- automatic temperature regulator.

The greater part of these components was combined structurally into one unit, in which the ventilator, the heat exchanger with the device for collecting the condensate, and the automatic temperature regulator were mounted.

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The automatic air-temperature regulator consisted of a sensitive element and a drive mechanism which, depending on the temperature set on the adjuster by the cosmonaut, changed the amount of air flowing through the heat exchanger. The accuracy with which the air temperature could be maintained was $\pm 1.5^\circ$.

Also installed in the cabin was an emergency heat-regulation system, based on evaporation an air circuit, opened. The system was activated when the air temperature in the cabin accidentally reached 35°

The unit for control of the parameters of the gaseous medium in the cabin consisted of the following:

- automatic O_2 and CO_2 gas analyzer;
- air humidity meter;
- air temperature gauge;

The arrow indicators of all these instruments were mounted on the cosmonauts instrument panel.

In order to observe the air regeneration and conditioning system, and also to monitor the state of the cabin's gaseous medium during flight, the system was designed for radiotelemetric check of the basic parameters characterizing the operation of the system aggregates and the state of the artificial atmosphere.

All this information permitted timely analysis of the functioning of the air regeneration and conditioning system even when it was necessary (in emergency situations) to make a correct decision as to maintenance of the necessary conditions.

From the time we started developing the life-support systems until the first flight of the Vostok spacecraft-satellite was accomplished, they underwent a series of ground experiments in hermetically sealed chambers and in mockups of the Vostok in which test subjects participated. In these experiments we studied and tested mock-up and experimental models of the system. The duration of the experiments was 1-15 days. The conditions under which some of the experiments were conducted were as close as possible to flight conditions.

After the series of laboratory tests and the appropriate improvements were made, flight models of the systems were also tested in spacecraft-satellites with live animals on board.

All these experiments made it possible to determine the features of the system, its operating schedules and the possible character of changes in the parameters of the gas medium as a function of the duration of the experiment and the heat conditions.

Simultaneously we studied problems concerning the state of a human being during prolonged confinement in the closed space of a sealed cabin in the case of an artificial gas medium produced by the regeneration system and also the air conditioning.

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The environmental conditions prevailing in the mockup of the Vostok while conducting these experiments were characterized by the following limiting values for the basic parameters:

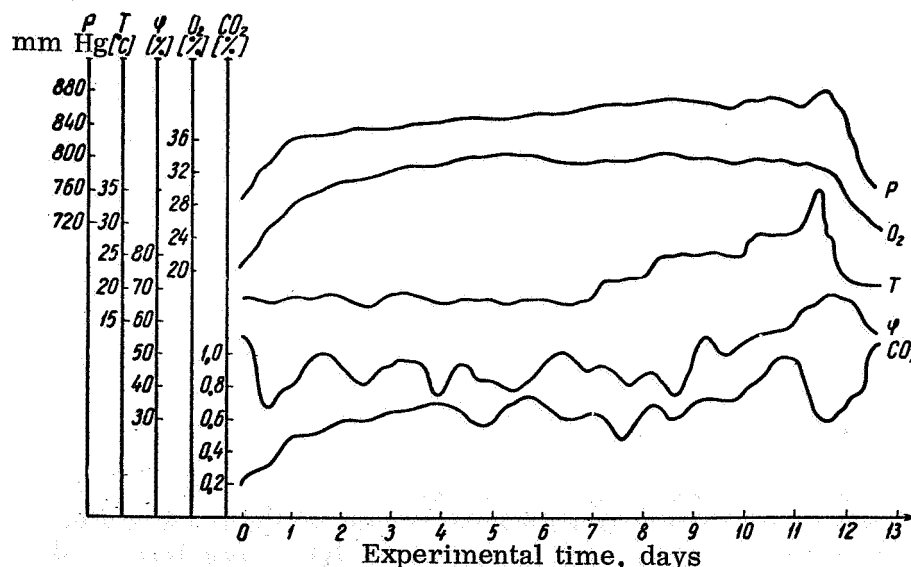


Figure 2. Nature of the Variation of the Environmental Gas Parameters in the Sealed Cabin of a Vostok Mockup During a Prolonged Experiment.

P—Pressure of the Gas Environment, mm Hg; T—Temperature of the Gas Environment, °C; ϕ —Relative Humidity; O_2 —Oxygen Concentration, %; CO_2 —Carbon Dioxide Concentration, %.

- barometric pressure: 740-900 mm Hg;
- air temperature: 15-35°;
- relative humidity: 32-75%;
- O₂ concentration: 21-33% (150-300 mm Hg);
- CO₂ concentration: 0.3-1% (2-9 mm Hg).

For purposes of illustration Fig. 2 shows a graph of the variation of the parameters of the gas environment in a 13-day control experiment.

The experiments we conducted led us to believe that prolonged confinement of a human being in the Vostok cabin while clothed in a space unit would not cause appreciable changes in the physiological functions.

In all the experiments the state of the test subjects remained satisfactory. Insofar as the cardio-vascular system and respiration are concerned, no appreciable changes were observed even when the air temperature was intentionally raised to 35°. The body temperature of the test subjects fluctuated in the range 36-37°. Throughout the experiments the test subjects reacted adequately to stimuli and carried out the tasks set by the experimenters accurately and timely.

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According to the data of the medical examination, the state of health of the test subjects after the experiments was declared to be satisfactory.

After carrying out the final series of tests, the life-support systems were authorized for the first flight of man in space. In accomplishing this flight the system functioned on the earth and in flight for a total of 5 hours. Within this period the environmental gas parameters in the airtight Vostok spacecraft-satellite cabin varied in range:

- pressure: from 750-755 mm Hg;
- temperature: from +19 to +20°C;
- humidity: from 62 to 69%;
- O₂ concentration: from 21 to 22%;
- CO₂ concentration: from 0.4 to 0.6%.

All system components functioned without failure.

The subsequent prolonged flight experiments on Vostok spacecraft confirmed our conclusions. The system successfully supported the flights of the Vostok spacecraft with the pilot-cosmonauts G. S. Titov, A. G. Nikolayev, P. R. Popovich, V. F. Bykovskiy and V. V. Tereshkova.

In all five flights the regeneration and air-conditioning system functioned faultlessly and provided the necessary conditions in the cabins of Vostok-2, Vostok-3, Vostok-4, Vostok-5, and Vostok-6.

Operational control of the systems in all flights was automated, and the cosmonauts did not have to resort to manual regulation, except for the temperature, which they adjusted in accordance with their sensations of heat.

Of all the flights accomplished, the longest was that of Vostok-5 with cosmonaut V. F. Bykovskiy.

Since the length of faultless operation is the most important characteristic for evaluating the regenerating and air-conditioning system, we can restrict ourselves to an analysis of the functioning of the Vostok-5 system and can consider the graph showing the variation of the environmental-gas parameters in the cabin for this flight (Fig. 3).

As follows from the graph, in the first two days the O_2 concentration rose and reached a value of 29% (226 mm Hg) toward the end of the second day. Subsequently, during the rest of the flight, the O_2 concentration did not exceed this value and varied in the limits 28-29%.

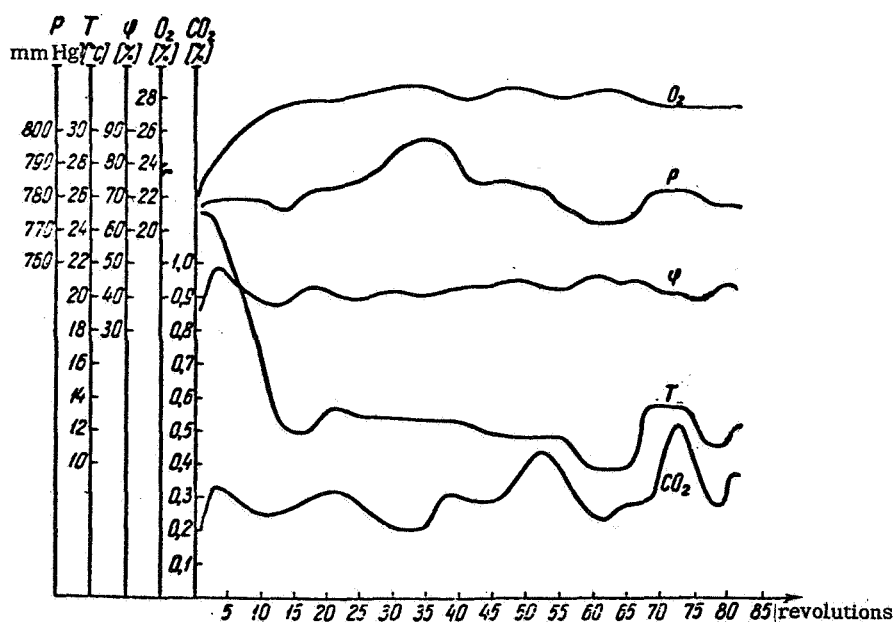


Figure 3. Nature of the Variation of Environmental-Gas Parameters in the Airtight Cabin of Vostok-5 with the Cosmonaut V. F. Bykovskiy:

P—Pressure of the Gaseous Medium, mm Hg; T—Temperature, °C;
 ϕ —Relative Humidity; O_2 —Oxygen Concentration, %; CO_2 —
 Carbon Dioxide Concentration, %.

The CO_2 concentration in the cabin's atmosphere varied in the limits 0.24-0.57%. The air humidity fluctuated during the flight in the limits 42-56%.

The temperature within the cabin at the start of the flight was +26°. In the first few days it decreased to +13° and held steady during the rest of the flight in the range +11 to +14°.

The nature of the change in air temperature and oxygen concentration essentially determined the total pressure of the gas medium within the cabin. It varied insignificantly (775-800 mm Hg).

Thus, during the flight the parameters of the ambient medium in the air-tight cabin of Vostok-5 kept within the limits of comfortable conditions. This favored to a significant degree investigation of the effect of weightlessness on the human organism. All system components worked without failure.

During the flights of the other Vostok spacecraft the conditions in the air-tight cabins did not differ appreciably from those described above. The data from post-flight analyses of the reduction of the regenerative agents and of the dessicants made it possible to determine the average hourly exchange of the cosmonauts and the amount of moisture liberated; these are given in the following table for each cosmonaut.

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TABLE. Average Hourly Exchange and Moisture Liberated

Cosmonaut	Absorption l/hr	CO ₂ liberated l/hr	H ₂ O generated g/hr	Respiration factor
A.G. Nikolayev	17.6	15	40	0.86
P.R. Popovich	20	17	47	0.85
V.V. Tereshkova	17.3	14.1	23	0.82
V.F. Bykovskiy	17.5	14.5	33	0.83

The results of operation of the regenerating and air-conditioning systems of the Vostok spacecraft in ground as well as flight experiments once again demonstrate the high qualities and reliability of such systems in providing for the necessary conditions in spacecraft cabins.

During the 3-cosmonaut space flight in the Vostok-3, the air regenerating and conditioning system functioned a total of 28 hours, 4 of them during the launch period while preparing for the flight. The cabin was sealed one hour before launch of the spacecraft. The pre-launch measurements indicated that the system was functioning normally and ensured the prescribed environmental parameters. After pressurizing the craft, the air temperature in the cabin was +17° the relative humidity -47%, the partial O₂ pressure 152 mm Hg; the CO₂ concentration was below 1%, and the pressure was 762 mm Hg.

During the flight all the parameters of the gas environment fell within the limits of the prescribed norms. Thus, the pressure varied in the limits 770-804 mm Hg, the temperature fluctuated from 15 to 22° (the cosmonauts were in sport clothes without space suits), the air humidity was 67-78%, the partial O₂ pressure varied from 158 to 188 mm Hg, and the CO₂ concentration was about 1%.

Investigations of the gas exchange and moisture liberation of the cosmonauts were made during the space flights from the results of analysis of the regeneration agents and from the dynamics of the change in concentration of the CO_2 , O_2 and moisture in the cabin's atmosphere. These studies indicate that the specific spaceflight conditions do not have any significant effect on the energy expenditures, rate of oxygen intake and liberation of CO_2 and H_2O . Deserving of attention is a certain tendency toward a decrease in the basic exchange indices, which obviously shows up more clearly during prolonged space flights.

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The food ration worked out for the Vostok and Voskhod spacecraft is apparently completely sufficient insofar as calorie intake and composition of the foods is concerned. Account must be taken, however, of a certain increase in intensity of protein exchange, which was observed in the cosmonauts after the flight, and also the increased vitamin requirements, especially of vitamin B-6.

The peculiarities of exchange of substances in spaceflight conditions require further investigation, especially in the case of long-duration flights. The results of these studies may be to introduce correctives to the food ration of the cosmonauts, which may be considerable for the support of long-range space excursions.

EFFECT ON THE ORGANISM OF PROLONGED
CONFINEMENT (100 days) IN A PURE OXYGEN
ATMOSPHERE AT OVERALL PRESSURE
OF 198 mm Hg*

N. A. Agadzhanyan, Yu. P. Bizin, G.P. Doronin,
A.G. Kuznetsov and A.R. Mansurov

In connection with the development of cosmonautics, considerable importance attaches to investigations relative to prolonged confinement of a human being in artificial atmospheres. In particular, of great theoretical and practical interest are investigations aimed at clarifying the possibility of prolonged exposure of the organism to an atmosphere consisting of pure oxygen at an overall pressure which excludes the toxic effect of this gas.

In recent years the problem of using a single medium consisting of a single gas (oxygen) in habitable spacecraft has been widely discussed in the American press.

Schaefer [12] states that among U. S. physiologists the opinion has been expressed that in spacecraft launched for a flight period of no more than two weeks it is expedient to create and maintain a gas medium consisting of a single gas, namely, oxygen. These recommendations were applied in the Mercury and Gemini programs, which were intended for two-week flights. In the Apollo spacecraft, which are intended for longer flight periods, it was first planned to use a gas medium consisting of 50% O₂ and 50% N₂ at an overall pressure of 362 mm Hg.

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But subsequently, as reported by Nonoshita [9], it was decided to use a single-gas (oxygen) atmosphere for Apollo also, in view of the necessity of reducing the launch weight of the craft.

In the opinion of the majority of authors, a "single-gas" medium has a number of advantages which are attracting the attention of designers and physiologists. When such a medium is used the cabin pressure can be reduced to 1/4 the standard atmosphere, resulting in the possibility of considerably reducing the cabin weight. At the same time the system for regenerating and regulating the gas medium is appropriately simplified, gas escape from the cabin is reduced to a minimum, and the danger of the development of aeroembolism in the cosmonauts during decompression is completely eliminated. Wherever the struggle to reduce the launch weight of a spacecraft has been a serious problem, the interest in such a type of gas medium is understandable.

The positive qualities of the gas medium being studied are accompanied by serious negative ones, and therefore use of such a medium must be approached with great caution; the problem as a whole has been but little studied and the application of insufficiently founded recommendations always involves hidden dangers.

*Report presented at the Second Internat. Symposium on Basic Environmental Problems of Man in Space, Paris, France, June 14-18, 1965.

It is well known that respiration of pure oxygen raises the danger of the appearance of atelectasis of the lungs, which is deleterious to blood oxygenation and creates the prerequisites for spot inflammation in the lungs. Even at a low partial pressure, pure oxygen has a slight irritating effect on the upper respiratory tracts.

Furthermore, the absence of inert nitrogen gas in the cabin environment considerably increases the danger of fire in the spacecraft; in flight situations this may have fatal aftereffects for the crew.

It is still far from clear whether the organism can survive and evolve for a long period of time in an atmosphere deprived of nitrogen. Whether this gas has any kind of relation to intrinsic physiological and biochemical processes of the organism remains a mystery to science.

Experimental study of such a medium on people in a pressure chamber under the rarefied conditions corresponding to altitudes of 8,400 and 10,200 m was carried out by D. Heather [11]. In experiments lasting 14 and 17 days this author observed in the test subjects symptoms of irritation of the respiratory tract and of the lung tissue; a reduction in body weight was noted in most of them. A more complete investigation of this problem was carried out on people confined in a pressure chamber for 30 days at an altitude of 5500 m and for 17 days at 10,000 m. The purpose was to study the effect on the organism of a rarefied atmosphere in the absence of an inert gas and also the effect of prolonged inactivity and of isolation [7]. Observed were a drop in diastolic pressure, extended pulse recovery times during the orthostatic test, a reduction in the vital capacity of the lungs, and symptoms of irritation of the respiratory tract and of the mucous membranes. The loss of body weight by the test subjects reached 2.8-3.6 kg in the 30-day experiments and 2 kg over 17 days. A decrease in water content was observed in the tissues of the organism, despite the loss of water, the fat content in the organism rose.

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In McHattie and Rahn's experiments [8], it was demonstrated that in a single-gas medium with a total pressure of 197 mm Hg mice survive and have a normal yield of offspring. This gave them justification to suggest that the absence of nitrogen in the atmosphere has no effect on the course of the most important vital processes.

Judging by Allen's tests [4], however, a categorical denial of a biological role for nitrogen in the organism of animals is premature. He found that the vascular system of chicken embryos does not develop in a one-gas (oxygen) medium at a pressure of 150 mm Hg and suggests that the reason for this is the lack of nitrogen in the gas medium. The necessity of further study in this direction is obvious.

Soviet specialists are guided by the principle of maximum caution in solving problems relating to a choice of the atmosphere for spacecraft. The choice of the gas medium must be scientifically founded. The medium must correspond to reasonable comfort requirements, must be harmless to the organism and must permit uninterrupted regeneration by reliable technical devices. It would be erroneous, however, to believe that a gas medium can be selected for spacecraft that would be equally suitable for any conditions.

Experience gained with the Soviet satellites Vostok and Voskhod in using an atmosphere whose parameters are close to the ground atmosphere has proved itself in many respects. Apparently there are no serious objections to continued use of an atmosphere similar in composition and pressure to the earth's atmosphere in short-duration orbital flights. At the same time interest in finding broader technical and biological possibilities for life support of a human being in space raises the question of the necessity for studying different variants of artificial atmosphere.

The aim of the present paper was a prolonged (100-day) all-around study of the effect on the organism of an atmosphere of pure oxygen at a total minimum pressure and a sufficient supply of this gas for animals.

METHOD

The experiments were carried out on white rats in a pressure chamber provided with a life-support system permitting maintenance of the prescribed parameters of the gaseous medium: O_2 content - 5%, CO_2 content - 0.3 to 0.5%, temperature 20-23° relative humidity - 50 to 70% water and food were supplied to the animals by means of a semiautomatic system. The feed for the rats consisted of 2/3 millet and 1/3 oatmeal. Four times a month the animals received bread, meat and polyvitamins.

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Equipment existed for removal of deleterious impurities from the air of the chamber, so that the amount of ammonia, CO_2 , hydrocarbons and other toxic products did not exceed the maximum permissible concentrations. Each animal cage has a sub-floor which was filled regularly with silicagel to absorb the urine. The structure of the chamber permitted the personnel to enter the chamber and leave it during the course of the experiment without disturbing the state of the gas medium.

To prevent aeroembolism the chamber was decompressed from 760 to 198 mm Hg by stages.

Kept under observation were 203 animals: of these 148 were experimental and 55 control animals. The same food and water schedules were maintained for both groups.

Studied were the behavior and over-all state of the animals, the higher nervous activity, the weight dynamics, certain aspects of the water-salt exchange, biological indices of the blood, changes in the positive elements of the peripheral blood, and morphological changes of the inner organs.

The results of observation show that no serious changes due to the effect of the gas medium being studied were noted in the overall behavior and state of the animals that might endanger their life or might cause disruption of the activity of the most important systems of the organism. Throughout the experiment the animals preserved sufficient nutritional excitability and reacted adequately to the surrounding laboratory situation.

RESULTS

Conditioned Reflexes. An effective automatic arrangement was developed.

The aim of the motor reactions was worked out by the method described in the work of L. G. Voronin and A. V. Napalkov [1]. In each test we used a stereotype made up of 18 positive chain stimuli and 6 conditionally inhibitive.

The use of this method permits investigation of subtle processes of analysis and synthesis of complex stimuli acting in a specific sequence on the organism. By doing so the physiological experiment turns out to be as close as possible to the natural relationships between the organism and the external medium, in which the leading role in adaptation is due not to simple conditioning signals, but to the effect of complex sets and series of stimuli.

During the first days of confinement in the medium being studied the rats exhibited some increase in their orientive - investigatory activity, an increase in the amount of between - signal reactions as the overall motor activity increased. At the same time, the overwhelming majority of applications of the chain stimulus was accompanied by a distinct chain motor reflex. A lack of reaction was encountered only exceptionally and only during the first month of the experiment.

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Without doubt this indicates that in the case of one-gas oxygen medium being studied, analysis and synthesis of the series of prepared food-acquisition motions was almost entirely uninterrupted.

Another pattern was observed when studying, in the same situation, conditioned disinhibition, evolved on the basis of a series of positive signals. It was discovered that if an obstacle is placed in the way of accomplishing a positive food-acquisition reflex and if the animal is taught to actively remove the obstacle in response to an additional signal, in a normal situation the animals rather quickly acquire the capability of timely execution of this action. Inadequate reactions were a rare phenomenon.

Under artificial atmospheric conditions, the reactions of the animals to the conditioning hindrance were inadequate; the percentage of adequate reactions drops. The drop is more pronounced during the first and, in part, during the second month the animals were exposed to the experimental conditions. In a number of cases the animals did not perceive what was intended by the signal for the additional component of the conditioning hindrance and executed motions which were governed by the stereotype of the positive series. In this case they did not receive food and returned to the starting point of motion, where they awaited the next signal.

In the second half of the experiment we observed a gradual standardization of the reactions of the animals of conditioning stimuli, and the data obtained in the aftereffect period almost coincided with the results of the control period.

The appearance of inadequate reactions to the conditioning hindrance signal is considered as the result of weakening of the process of active internal inhibition.

Change in Weight. Throughout the first half of the experiment (50 days) a considerable loss of weight was observed in the animals, amounting to 25% of the original body weight. After 55 days the weight of the animals begins to recover and toward the end of the experiment the gain in weight by the experimental rats is greater than that of the control animals. At this time the weight balance of the experimental rats (72 g) exceeded the weight balance of the control rats (56 g) by 16 g.

There is reason to believe that the negative weight balance is due to an increase in water lost by the organism because of the low-pressure effect of the ambient atmosphere.

In the work of Kuznetsov, Van Lier, Swann and Collings [2, 6, 10] a decrease in diuresis, an increase in the separation of sodium chloride with the urine and an increase in loss of body weight were observed during the experiment on the animals. In the opinion of the authors, these symptoms were due to a state of acute hypoxia of the organism as well as to considerable hyperventilation of the lungs, which always occurs in such cases, causing a sharp increase in the loss of moisture through the respiratory tract.

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In the present work the oxygen supply of the animals was sufficient and water losses by the organism could be traced only to the independent effect of the low-pressure atmosphere. The literature does not contain direct, well founded proof of the effect of low barometric pressure on the increase of moisture lost by the organism. It is known only that water evaporation increases under these conditions due to the decrease in the number of collisions between the evaporating molecules and the molecules of the gas whose concentration has been reduced because of a drop in pressure. This is what was shown by the direct measurements of H₂O evaporation at normal and increased barometric pressure made in the present work by A. I. Shaposhnikov and B. S. Perepletchikova:

Parameters	760 mm Hg	198 mm Hg
Temperature, °C	20-23	20-25
Humidity, %	45-65	42-75
Amount of evaporated water, g ..	1125	2150
Evaporation rate, g/cm ² /hr	2.5	4.4

From these data it follows that the amount of evaporated water from equal surfaces in the case of low pressure is almost double that in the case of normal pressure.

If the drop in weight of the animals is attributed to increased removal of water, it is only natural that this should be reflected in the water content of the tissues, above all in such tissues as the skin, muscles, and liver, which are usually considered to be the repository of liquid in the organism.

These experiments showed that the water content* of the skin and muscles of the animals decreased, coinciding in time with the drop in body weight of the

* The H₂O content in the tissues was determined by the weight method.

animals. These changes were expressed in clearer form in the skin tissue, in which the water content dropped by almost one-half in 15 days of experiment. The drop in water content of the liver, muscles and blood was insignificant.

It would seem that all these facts support the suggestion that the drop in weight of animals and men in a rarefied atmosphere may be attendant upon an increase in H_2O release by the organism from the surface of the skin and lungs.

The process of H_2O release by evaporation is, however, a phenomenon of the physical order, and therefore we should logically expect it to continue throughout the period the organism is exposed to rarefied atmospheric conditions. As was pointed out above, however, the animal weight was observed to drop only during the first half of the experiment. In the second half the weight of the test animals continuously increased and toward the end of the experiment it exceeded the weight of the control animals. Obviously, the considerable fluctuations in animal weight observed under a rarefied atmosphere cannot be explained by changes in water liberation alone. Most likely, the studied phenomena are also closely related with changes in the exchange processes.

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Here it is important to note that in themselves the phenomena of a decrease and increase in weight of the animals under these conditions are of great scientific interest in another respect also: they indicate the presence of an active factor under these conditions whose physiological role has been denied in the literature up to the present time. The facts show that low atmospheric pressure (at normal pO_2) itself has a specific effect on the organism, and adaptation to existence in a new medium evolves gradually in the organism. The time required for adaptation is apparently determined by the degree of atmospheric rarefaction.

According to our tentative data, the time of adaptation to confinement in an atmosphere of normal pO_2 and to an overall decrease in atmospheric pressure to 308 or 198 mm Hg took 30-35 or 55-60 days, resp. [3]. It is interesting that the cycle of change in the composition of the peripheral blood was completed in approximately the same period: the observed increase, in the blood, of the content of hemoglobin (120%), erythrocytes (134%), reticulocytes (160%) was maintained at this level for 43 days. On the 58-th day the blood indices returned to the original level and remained there until the end of the experiment (N.I. Yezepchuk).

The Biological Role of Nitrogen. It is also necessary to say something about observations incident to the use, for animals, of a gas medium consisting of a single gas (oxygen), the inert gas nitrogen being absent from the medium. The observations showed that rats survive in a single-gas oxygen medium at a pressure of 198 mm Hg for 100 days and have a normal yield of offspring. Of interest are the observations which indicate that the pregnancy period of the animals under these conditions increases by 5-7 days. Although the small number of observations does not give us the right to exclude the random element in the case, the known agreement of our data with those of Allen [4] on the lag in development of the vascular system of chicken embryos under the same conditions gives us reason to believe that atmospheric nitrogen plays an important part in the development of vitally important functions of the organism. In addition the significance of the absence of nitrogen in a gas medium was studied in regard to the formation of atelectasis of the lungs.

In the process of morphological study of the animals (V. A. Vinogradov) slightly pronounced local atelectasis of the lungs was observed in the marginal zone; this was more pronounced in animals exposed to the one-gas oxygen medium in the first two days. Atelectasis of the lungs was not observed in animals subjected to a morphological examination at later periods, and therefore the observed collapse of lung tissue in animals was reversible. No signs of toxic poisoning or irritation of the lung tissue by oxygen were observed.

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Throughout the experiment, the pO_2 of the blood was kept at a high level; the pCO_2 was somewhat lowered (Ye. A. Kovalenko).

Change in Microflora. According to observations by N. N. Sitnikova, the quantity of microflora in the chamber atmosphere during the experiment increased by a factor of approximately 5; the microbe pattern shifted toward the side of prevalence of the forms of microorganisms which are more stable to the action of the environment, that is, spores, aerobes, and fungi appeared. Here we see the form of interaction between an organism and a medium in which the direct effects of the medium on the organism and the inverse effect of the organism on the environmental medium are combined.

CONCLUSION

Prolonged (100-day) confinement of animals in a one-gas oxygen medium at a total pressure of 198 mm Hg presents no danger to the life and overall state of the organism, which indicates that it is possible to use such a medium for practical purposes.

At the same time it was demonstrated in our work that distinct changes in a number of important physiological functions of the organism arise during prolonged confinement in a gas medium with a low overall pressure and normal oxygen content. The phenomena gradually smooth out and in 50-60 days a period of normalization of the organism's functions sets in, which testifies to the evolution of adaptive phenomena.

All this proves that decreased pressure of the gas medium has independent biological significance which must be taken into account when studying the problem of the habitability of spacecraft in the case of a rarefied atmosphere.

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CERTAIN FUNCTIONS OF THE CENTRAL NERVOUS SYSTEM AND
GAS EXCHANGE DURING PROLONGED CONFINEMENT OF
ANIMALS IN A HYPEROXIC
HELIUM ENVIRONMENT

A. G. Gironkin and G. V. Troshikhin

The problem of replacing nitrogen in the air by helium in the atmosphere of a spacecraft cabin has not as yet been solved. A number of arguments is being advanced in favor of such a substitution, based on the peculiarities of the physical-chemical properties of this gas.

The high fluidity of helium favors a decrease in the supply of energy required to ventilate a gaseous mixture in conditioner systems [5, 8]. The low solubility factor in water and fat reduces the danger of decompression disorders during emergency depressurization of the cabin [5, 8]. The high thermal conductivity (the coefficient of thermal conductivity of helium is approximately 6 times greater than that of air) creates favorable conditions of heat transfer for the cosmonaut [5, 8].

Of indisputable interest for space flights is also the creation of a helium atmosphere in a space ship or space suit with a higher oxygen content, since the positive sides of helium and oxygen are combined in this variant.

As we know, respiration of oxygen promotes an increase in stability of the organism to g-loading and acceleration [7], reduces the danger of aeroembolism and of acute oxygen starvation [6] in case of cabin depressurization, improves sleep [3], increases efficiency [10], etc.

The existing papers on the study of the effect of helium on biological objects are, however, still insufficient for an evaluation of the possibility of prolonged safe existence of man in helium-oxygen media. There is an almost complete lack of research on the problem of the effect on the organism of helium environments enriched with oxygen. In one of the Soviet papers [4] data are presented on the increase of the toxic effect of oxygen mixed with helium (80% oxygen, 20% helium). /209
Incidentally, of greater interest in spaceflight practice are investigations of the effect on the organism of He-O mixtures with an oxygen content lying within the limits of the upper safety range (60% oxygen) for human respiration [9].

On the basis of what has been said, we carried out experiments devoted to estimating some physiological indices of the central nervous system and of the metabolism of mice confined for 20 days in helium-oxygen and nitrogen-oxygen environments enriched with up to 60% oxygen. For control purposes we used animals exposed to atmospheric conditions for the same period.

We studied the dynamics of evolution of conditioned reflexes and of the gas-exchange level. The experiments were conducted in three hermetically sealed chambers provided with rubber sleeves and locks. The chambers were linked up with a closed air regeneration system, which ensured complete purging of the waste products of the animals from the air. Oxygen was fed automatically, as required,

from a rubber container through a gas meter. The temperature of the gaseous environment in the chamber was maintained in the range of 19-21°. The tests were performed on 60 white mice, males, of the line CC57W, three months old. In the chambers the mice were contained in special cages, 10 each, which were equipped with automatic feeders and drinkers. Each chamber contained a modified Aleksandrov-Tsibina rig for study of the conditioned defense reflexes. The rig was made of a box separated into two halves by a partition with a passageway. Electric current was transmitted to the floors of each half of the box, the floors consisting of wires. The rubber sleeves made it possible to transfer the mice from the cage into the apparatus without disturbing the gas composition of the chamber. As a conditional stimulus the light from a 6-V bulb. At the 11-th second of presentation of the conditional stimulus, electric current was transmitted (3-5 V); as a result the mice ran into the other half of the apparatus. Ten such combinations were executed daily.

The conditioned - reflex activity was evaluated over the number of days required to form a conditioned reflex, and with respect to the average escape time (in sec). The reflex was considered to have set in when the animal ran into the currentless half of the box ten times in succession (100% correct responses) in response to the conditioning signal. The conditioned reflexes were determined daily in ten mice in each group.

The gas exchange was determined with the mice continuously confined in the respective environments. The oxygen needs were computed daily for a total of 17 hours, during the period 4:00 PM to 9:00 AM, from the indications of the gas meter. The gas composition in the chambers (oxygen and carbon dioxide) was checked daily with a Haldane instrument and the helium with a GEUK instrument which we modified.

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The carbon dioxide impurity during the experiments was from 0.1 to 0.7%; the nitrogen content in the helium-oxygen mixture reached 2.5 to 5%, in the hyperoxic mixture it fluctuated in the range 37-43% and in the air between 77.5 and 80.5%.

The experiments we performed demonstrated that animals subjected to a hyperoxic medium, diluted either with helium or nitrogen ("helium" and "nitrogen" mice), exhibited retarded formation of conditioned reflexes and a reduction of their running speed as compared with the control animals (Fig. 1).

From Fig. 1 it is evident that both groups of experimental mice exhibited a distinctly retarded evolution of conditioned reflexes and reduction of the running speed. It turned out also that the conditioned reflexes of the "helium" groups evolved somewhat slower than in the "nitrogen" mice. Complete evolution of the conditioned reflexes was accomplished in the "helium" animals on the 12-th day, on the average, and in the "nitrogen" animals on the 11-th day, but the difference is statistically unreliable. In the control "air" mice evolution of conditioned reflexes ended on the 7-th day; the difference is statistically reliable between the experimental and control groups.

This same characteristic was also observed in the dynamics of changes in running speed.

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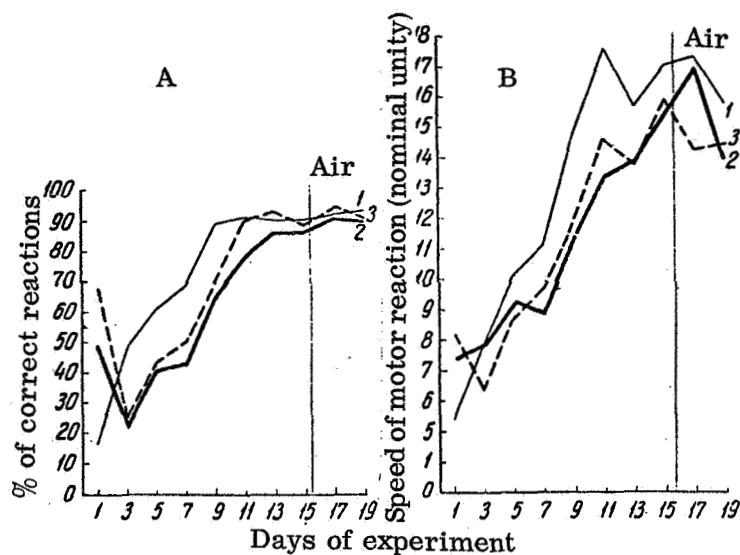


Figure 1. Dynamics of the Evolution of a Conditioned Reflex (A) and Speed of Motor Reflex (B) in Mice in an He-O₂ and N₂-O₂ Medium With a 60% O₂ Content.

1—Control; 2—He-O₂ Group of Mice; 3—N₂-O₂ Group of Mice.

The considerable lag in evolution of conditioned reflexes in the case of the animals which were subjected to the helium-oxygen medium is obviously attendant upon the high thermal conductivity of helium, which facilitates cooling of the animals, since the heat comfort zone for animals in a helium environment shifts by 3–4° [1].

The retardation of the formation of conditioned reflexes and of the running speed in these environments may have also depended on the direct effect of oxygen, which is proved by experiments with a nitrogen-oxygen mixture containing 60% oxygen. In some measure our data agree with the published data on a reduction of the conditioned - reflex activity of dogs when breathing air with a 60% oxygen admixture [7].

The mice exposed to an oxygen - rich helium environment revealed not only a change in the conditioned - unconditioned reflex activity, but also appreciable displacements of the gas-exchange level. The confinement of animals in such a medium was accompanied by a considerable augmentation of gas exchange during the entire course of the experiment. A less pronounced increase in gas exchange was observed in the "nitrogen - oxygen" mice; intensified gas exchange was noted for the first three days, and then the level dropped to the normal values. Subsequently, except for a few fluctuations, the oxygen requirement again increased and remained at the higher level until the end of the experiment (Fig. 2). The weight of the animals did not change appreciably during the entire experiment.

A considerable contribution is apparently made to the mechanism of increased gas exchange of mice confined in an oxygen-rich helium medium by the high thermal conductivity of the helium, facilitating cooling of these animals. Not excluded either is the possibility of the slight cooling effect of oxygen, since its heat

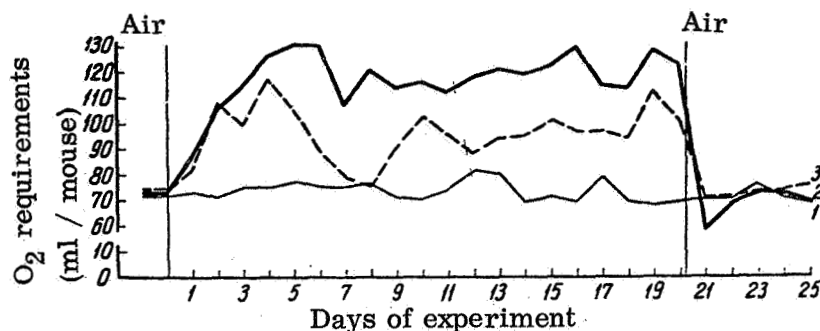


Figure 2. Dynamics of the O_2 Requirement in Mice While Confined in a Hyperoxic Environment (60% O_2) Diluted With Helium and Nitrogen.
Notation as in Fig. 1.

conductivity is somewhat higher than that of air. In this physiological reaction some significance can also be attributed to the stimulating effect of helium [11] and oxygen [2] on the exchange processes. Most probably both these factors are related to the increase of gas exchange in animals exposed over a prolonged period to a helium-oxygen and nitrogen-oxygen medium with a high oxygen content. Without doubt, helium and oxygen exert a mutually stimulating effect on the gas exchange. This fact deserves attention and requires further experimental foundation in understanding the mechanism of the phenomenon we have discovered.

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HUMAN REACTIONS TO HYPOXIA AND HYPERCAPNIA WHEN BREATHING NITROGEN- AND HELIUM- OXYGEN MIXTURES

I. S. Breslav and Ye. N. Salatsinskaya

In recent years, as a result of the broad use of helium, particularly in submarine and space medicine, interest has arisen in the effects of this gas on the respiratory functions. It has been found that due to low density helium-oxygen mixtures facilitate breathing, especially if resistance in the respiratory tract is high and pulmonary ventilation is increased [4, 5, 7, 9].

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As yet, however, little is known as to how helium affects the reaction of the respiratory system relative to oxygen deficiency and excess carbon dioxide in the air mixtures being inhaled. The present paper is devoted precisely to this question.

As the integral index of the organism's reaction to this or that change in the composition of the inhaled mixtures we used the gas-preferendum method, namely, the active choice of preferred respiratory media [1]. Prior observations [2] have shown that man and animals usually prefer helium-oxygen mixtures to nitrogen-oxygen ones. In the same reference it was explained that in some cases of oxygen starvation (breathing in a closed space) a helium medium ensures more effective maintenance of blood oxygenation.

The present research was carried out on men and women aged 18 to 25 years.

The experiment was set up in the following fashion. The test subject sat in a chair and breathed through a half-mask equipped with valves which gave minimum resistance. After accommodation to the mask, the test began with a 5-minute period of breathing ordinary air. Then the test subject breathed the first gas mixture from a container for 5 min. Then he proceeded to the next mixture, also for 5 min. Following this the experiment continued for 15 min, during which time the test subject, controlling his own sensations, could himself switch to any of the two mixtures; a special tap was reserved for this purpose. The index of choice was the relationship between the intervals during which the person breathed the first and second mixtures.

The respiratory motions of the test subject, the respiration volume per min, the pulse rate*, and the oxygen saturation of the arterial blood were recorded during the experiment by the usual methods. Usually, the level of the indices being studied became more or less stable at the third or fourth minute of breathing each mixture. Therefore, everywhere in what follows we will give the values recorded at the 4-th or 5-th minute after going on to the given mixture.

* The pulse rate of the test subjects while breathing the different mixtures did not show statistically significant changes and is, therefore, not cited by us.

In each experiment one of the inhaled mixtures was taken nominally to be indifferent: the indices obtained during respiration of this mixture served as a control. The compared figures were processed statistically by the method of natural pairs of variants.

Three series of experiments were performed, in which we compared the effects of breathing nitrogen and helium mixtures with a normal and lower oxygen content, and also with various concentrations of carbon dioxide (Table 1). /214

TABLE 1. Respiratory Mixtures Used
in the Tests

Series	No. of test subject	Composition of the mixtures	
		indifferent (% of O ₂)	different (% O ₂)
I	12-15	21	21
		18	18
		15 } in N ₂	15 } in He
		12	12
		9	9
II	12	21 in N ₂	18
			15 } in N ₂
			12
			9
III	10	21 in N ₂	% CO ₂
			1.0
			2.5 } in 21% O ₂ + N ₂
			6.0
	10	21 in He	1.0
			2.5 } in 21% O ₂ + He
			6.0
	10	12 in N ₂	1.0
			2.5 } in 12% O ₂ + N ₂
			6.0
	10	12 in He	1.0
			2.5 } in 12% O ₂ + He
			6.0

In order to compensate for the effect of training and other factors, the experimental conditions were randomized if possible.

In the first series of experiments the test subjects breathed nitrogen and helium mixtures with a normal and reduced oxygen content. In each experiment the mixture presented for inhalation was nitrogen (indifferent) and helium (different), the oxygen content in both cases being the same. This permitted direct comparison of the reactions to the nitrogen and helium media (Table 2).

At a normal oxygen concentration, breathing of the helium mixture caused a small increase in breathing rate with a corresponding decrease in respiratory volume, which appears to be adaptation to breathing a less dense mixture: in such a case, increased breathing rate and shallow breathing are more economical [3]. The same phenomenon can also be observed when breathing hypoxic helium mixtures, although the observed changes are not everywhere statistically reliable. Oxygen saturation of blood in helium media did not differ essentially from the values obtained for analogous nitrogen mixtures. Under normal as well as hypoxic conditions, the test subjects invariably gave preference to helium mixtures: the time of respiration of these mixtures was always greater than the respiration rate of nitrogen mixtures. The probable reason for this consists in the lower amount of respiratory work required to maintain alveolar ventilation in the less dense helium medium.

In series II the test subjects were divided into two groups: one breathed only nitrogen mixtures, the other only helium mixtures during the test period. In each test the indifferent mixture was the one with a normal oxygen concentration, while the different one was the mixture with a lower content. In Fig. 1 the reactions of the test subjects are expressed in % relative to the indices obtained when breathing the corresponding (nitrogen or helium) indifferent mixture.

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The test subjects did not distinguish the mixture of 18% oxygen with nitrogen from air. The analogous helium mixture was even more frequently preferred to the indifferent mixture, despite the fact that oxygen saturation of the blood decreased. We assume that such a mixture, owing to the additional hypoxic stimulus, puts the more habitual load on the respiratory system of a human being than a helium medium with a normal oxygen content, which, judging from the oral accounts of the test subjects, seems to be unusually easy to breathe.

Beginning at 15% O_2 , pulmonary ventilation when breathing the nitrogen mixtures increased linearly as a function of the degree of reduction of the oxygen content. But in the "helium" group this rule is broken by the lag of the respiration volume per min at 12% O_2 , although the blood oxygenation in this group decreases in the same way as in the "nitrogen" group (nowhere do the differences reach statistically significant values). Possibly it is precisely because of the smaller volume of increase in ventilation when breathing the mixture of 12% O_2 with helium that the test subjects, judging from their reaction to choice, did not distinguish this mixture from the indifferent one, whereas the same mixture was explicitly avoided in the nitrogen medium.

In the case of more severe hypoxia (9% O_2) the difference between the groups with respect to all the indices disappeared. In particular, the negative reaction of the test subjects proved to be identical for the nitrogen as well as the helium mixture.

TABLE 2. Comparative Indices of Breathing Nitrogen and Helium Mixtures
With Normal and Reduced Oxygen Contents

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Indices	21% O ₂				10% O ₂			
	mean		difference		mean		difference	
	N ₂	He	D ± m	P	N ₂	He	D ± m	P
Breathing rhythm	17.0	17.6	+0.6±0.3	0.1	16.6	17.6	+1.0±0.3	0.01
Respiratory volume per min (l/min)	6.8	6.5	-0.3±0.2	H*	6.9	7.0	+0.1±0.2	H
Respiratory volume (l) .	0.40	0.38	-0.02±0.006	0.01	0.42	0.40	-0.02±0.01	0.1
O ₂ saturation of blood (%)	93.3	92.2	-1.1±0.9	H	91.0	91.2	+0.2±0.5	H
Breathing time by choice (min)	5.0	10.0	+5.0±2.1	0.05	5.0	10.0	+5.0±1.9	0.05

TABLE 2 (cont'd)

Indices	15% O ₂				12% O ₂				9% O ₂			
	mean		difference		mean		difference		mean		difference	
	N ₂	He	D ± m	P	N ₂	He	D ± m	P	N ₂	He	D ± m	P
Breathing rhythm	16.8	17.0	+0.2±0.4	H	15.9	16.6	+0.7±0.5	H	16.3	18.0	+1.7±0.8	0.05
Respiratory volume per min (l/min)	7.4	7.2	-0.2±0.3	H	7.6	7.4	-0.2±0.4	H	10.5	9.9	-0.6±0.4	H
Respiratory volume (l)	0.46	0.42	-0.04±0.02	H	0.49	0.46	-0.03±0.02	H	0.67	0.57	-0.10±0.04	0.05
O ₂ saturation of blood (%)	86.3	86.5	+0.2±0.5	H	83.5	83.6	+0.1±0.9	H	89.3	89.3	0±1.5	—
Breathing time by choice (min)	5.5	9.5	+4.0±1.6	0.05	5.8	9.2	+3.4±1.4	0.05	5.4	9.6	+3.2±1.5	0.05

*H - difference not reliable.

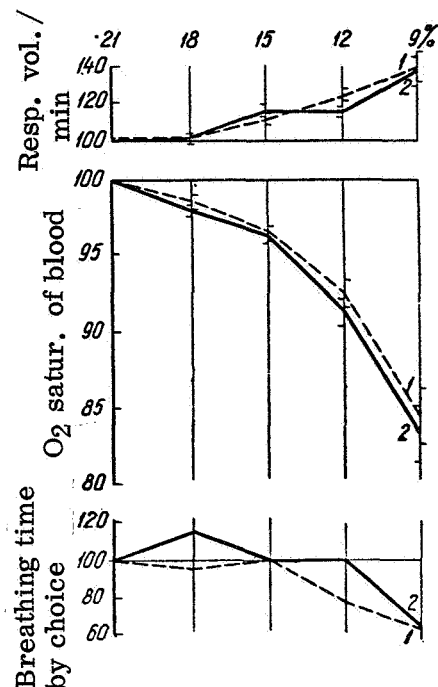


Figure 1. Reactions to Breathing Hypoxic Nitrogen - (1) and Helium - (2) Oxygen Mixtures (in % Relative to the Level When Breathing Mixtures With 21% O₂).

Reactions to Hypercapnia

In series III of the experiments, helium or nitrogen mixtures with a normal or reduced (12%) oxygen content served as the indifferent mixtures. Different mixtures were the same mixtures with additions of various concentrations of CO₂. As in series II, one group of test subjects received only nitrogen mixtures, the other only helium. Figure 2 reflects the reactions to the various hypercapnic mixtures. The indices are given in % relative to the values obtained while breathing the corresponding indifferent mixture.

As the curve of the respiration volume per minute shows, with a normal O₂ content the ventilatory reaction to CO₂ was more pronounced in the helium than in the nitrogen mixture. This can be explained by the already-mentioned facilitating effect of helium on breathing under conditions of increased ventilation. However, blood oxygenation increases even somewhat less during breathing of helium mixtures than nitrogen mixtures (at 2.5% CO₂ the difference is statistically reliable).

Perhaps the worse blood arterialization in the given case is explained by the incipient incompatibility between the increased respiratory volume and the lesser (pulmonary) blood circulation when breathing a normal CO₂ + He-O mixture.

The reaction to choice provides indirect evidence in favor of such an assumption. It is true, of course, that a slightly hypercapnic (1% CO₂) helium mixture was even somewhat preferred by the test subjects to the indifferent mixture, and this, by analogy with the slightly hypoxic mixture, may depend on the more "comfortable" nature of breathing in the presence of an additional (in this case hypercapnic) stimulus. But the helium group already exhibited an explicitly negative reaction to a mixture with a 25% CO₂ content, whereas no such reaction occurred in the nitrogen group. A 6% CO₂ content is distinctly avoided by the nitrogen group, but even more so by the helium group.

Under hypoxic conditions the breathing reaction to CO₂ was found to be almost the same in the helium group as in the nitrogen group. At the same time oxygen saturation of the blood when breathing mixtures containing 1% and especially 2.5% CO₂ increased greater in the helium group than in the nitrogen group. Judging from the respiration rate, the sensitivity of the test subjects to slight hypercapnia when breathing helium mixtures was reduced here: a 1% mixture was clearly preferred by the test subjects (in addition to the explanation given above, it must

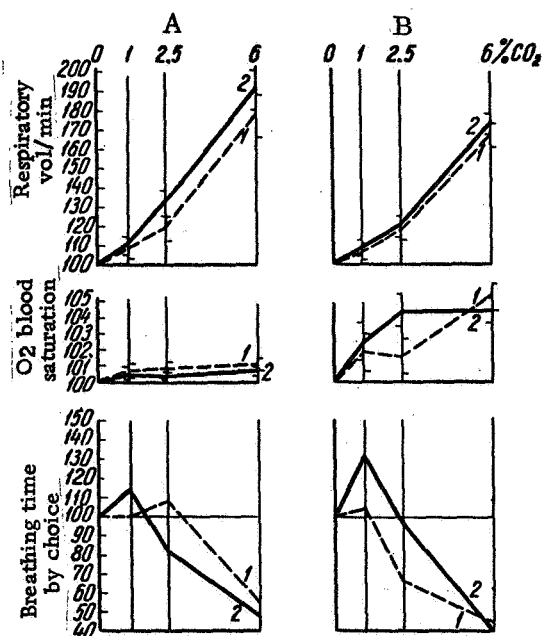


Figure 2. Reactions to Breathing Hypercapnic Nitrogen - (1) and Helium - (2) Oxygen Mixtures With a Normal (A) and Reduced (B) O_2 Content. Percentage Relative to the Level When Breathe in the Same Mixtures Without CO_2 .

also be kept in mind that in the given case ventilatory reaction to CO_2

assists in compensating for hypoxemia), but the 2.5% mixture did not call forth a distinct choice, while such a mixture had already been avoided by the nitrogen group. At the same time, the relations between all the indices (ventilation, blood saturation and choice) when breathing a mixture with 6% CO_2

turned out to be the same for both groups as noted under conditions of a normal oxygen content.

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If, taking these arguments into account, we intercompare the curves for oxygen saturation of the blood and the choice indices, as given in Fig. 2, we can note the following characteristic: wherever the hypercapnic mixture (nitrogen or helium) causes a greater increase in blood oxygenation, this mixture is less avoided by the test subjects. Saturation can be considered here as an indirect index of blood arterialization in the lungs and consequently also of the efficiency of removal of excess CO_2 . It is

natural that mixtures which result in a greater accumulation of CO_2 in the blood when inhaled also call forth a stronger negative reaction in man. As has been shown, in this respect the nitrogen medium proves to be more favorable for breathing mixtures with a relatively small percentage of CO_2 at a normal oxygen content, while the helium medium is better for a reduced oxygen content. Insofar as mixtures with 6% CO_2 are concerned, as we know when breathing such mixtures neither an increase in alveolar ventilation nor any other adaptive reactions of the organism are able to compensate for the state of hypercapnia [8] and therefore such a CO_2 concentration were absolutely rejected, whether in the nitrogen or the helium medium.

Thus it can be assumed that it is precisely the CO_2 strength of the blood, this extremely important regulator of respiration [6], which determines the capability of a human being to single out breathing mixtures with a high content of CO_2 .

It is not out of the question that the pCO_2 of the blood plays an important part also in the capability of man to avoid breathing hypoxic mixtures. Indeed, ventilatory reaction to a reduction in partial oxygen pressure in the air being breathed results in a state of hypocapnia, which can cause a negative reaction to a hypoxic medium. In fact, a 12% O_2 mixture with helium in our experiments increased the

respiration rate per minute less than the analogous nitrogen mixture, and therefore there should have been less hypocapnia in the test subjects. This is precisely the mixture that the test subjects of the "helium" group did not distinguish from a mixture with a normal oxygen content, whereas this distinction was clearly made in the nitrogen medium.

It goes without saying that the complicated reasons for the difference in reactions of a human being to hypoxia and hypercapnia in nitrogen and helium media require further research.

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PHYSIOLOGICAL EFFECT OF THE REPLACEMENT OF NITROGEN
IN THE AIR BY HELIUM IN THE CASE OF OXYGEN
DEFICIENCY AND HIGH CO₂ CONCENTRATIONS

A. G. Dianov

In the preceding investigations it was found that man could be confined for some time in a helium-oxygen medium in the case of a normal oxygen content and very slight concentrations of CO₂ [6, 7].

For the purpose of further study of the problem of the use of helium in the atmosphere of pressurized cabins it is expedient to investigate the effect of a helium-oxygen medium on the living organism under the conditions of oxygen deficiency and high CO₂ concentrations.

The most suitable experimental model for the solution of this problem is the exposure of animals to a helium-oxygen environment in a hermetically sealed chamber without atmospheric regeneration. At a result of vital activity of the organism in the atmosphere of the chamber the oxygen concentration will gradually decrease and at the same time the CO₂ concentration will rise. The available literature does not give indications that similar studies have been made.

PROCEDURE

The experiments were performed with male white rats weighing 116-120 g. Used in this work was the experimental arrangement outlined in Fig. 1.

Before beginning each experiment the test animal was attached to a wooden support. Sensors were fastened to the body of the animal to record the physiological functions. Electric wires from the sensors were soldered to the terminals of the switching panel placed on the detachable wall of the hermetically sealed chamber. The chamber, with a volume of 1190 cm³, was made of organic glass so that the animal could be observed in the course of the experiment. After the animal and support were placed in the chamber, it was hermetically sealed by pressing the detachable wall against it using a special clamping device. From the inside a mercury thermometer was inserted into the detachable wall to measure the temperature of the gaseous environment in the chamber. The top of the chamber contained tubes, one of which was designed to extract gas samples from the chamber, while the other was to measure the chamber pressure. The tubes rigidly attached the hermetic chamber to the top of the heat regulating chamber. The heat-regulating chamber was also made of organic glass. The temperature was maintained at the given level by means of a heat regulator.

The nitrogen in the chamber atmosphere was replaced with helium by ventilating the atmosphere with a helium-oxygen mixture consisting of 21% O₂ and 79% He. Ventilation was by an air pump. Before the ventilating gas mixture reached

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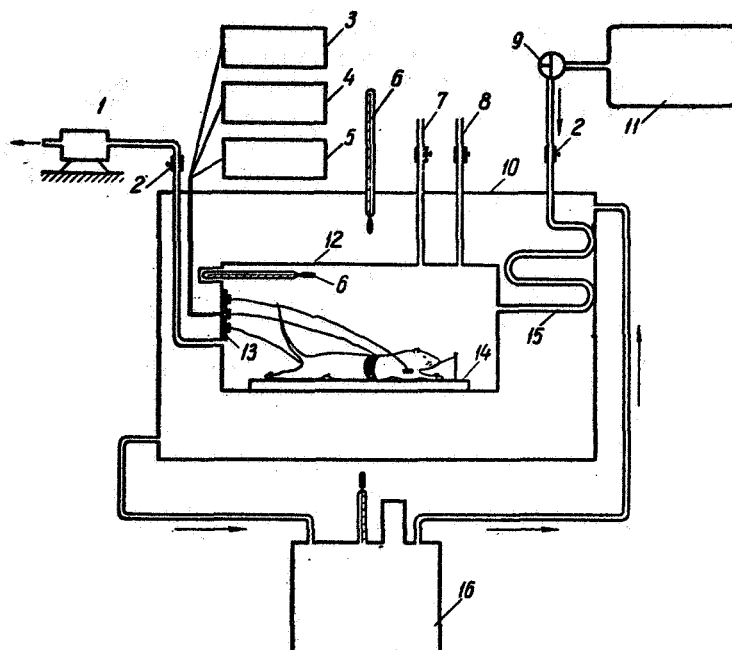


Figure 1. Block Diagram of the Experimental Setup.

1—Air Pump; 2—Clamps; 3—Electrocardiograph;
 4—Instrument for Recording the Respiratory Motions;
 5—Instrument for Body-Temperature Measurement;
 6—Thermometer; 7—Tube for Extraction of Gas Sam-
 ples; 8—Tube for Chamber-Pressure Measurement;
 9—Three-Way Stopcock; 10—Heat-Regulating Chamber;
 11—Rubber Container With the He-O₂ Mixture; 12—Her-
 metically Sealed Chamber; 13—Switch Panel; 14—Sup-
 port for Immobilizing the Animal; 15—Coil; 16—Heat
 Regulator.

the hermetic chamber it passed through a small coil, where it reached the pre-
 scribed temperature. In control experiments the hermetic chamber with the test
 animal was ventilated with air for 30 min. While performing the experiments in
 which atmospheric nitrogen was replaced by helium, the chamber was ventilated
 with air for 15 min, and then with the helium-oxygen mixture of the rubber con-
 tainer for 15 min. The transition from ventilation of the chamber with air to
 ventilation with the helium-oxygen mixture was accomplished by an appropriate
 turn of the three-way stopcock. After expiration of the indicated time, the
 gaseous medium of the sealed chamber did not differ in composition from the
 helium-oxygen mixture. The concentration of nitrogen and helium in the chamber
 was determined by means of electric gas analyzers of the "nitrograph" and "pul-
 moanalyzator" makes of the Dutch firm "Godart", while the concentration of oxygen
 and CO₂ was determined by means of an ORSA instrument. After the 30-minute
 period of chamber ventilation with air or with the helium-oxygen mixture, the air
 pump was disconnected, and the chamber was hermetically sealed by closing the
 clamps on the rubber supply and evacuation tubes.

In the course of the experiment we measured on the animals the body temperature, the breathing rate and the heart contraction rate, and we also determined the duration of life from the instant the chamber was sealed until breathing stopped. The indicated physiological indices were recorded for the first time after the animal was immobilized on the support, and then every 5 min during the experiment. The last record of the heart contraction rate and the body temperature measurement were made at the instant breathing stopped. Immediately after this the chamber atmosphere was checked to determine the concentration of oxygen and CO₂ at which the animal perished. For this purpose a gas sample was extracted from the chamber in an evacuated burette and was then analyzed on a Holden apparatus.

The experiments were carried out at chamber gas-medium temperature of 22, 27, 31 and 36°. At each of the indicated temperatures 10 control experiments were made in an ordinary atmospheric environment and 10 experiments in the helium-oxygen medium (in all 80 experiments).

EXPERIMENTAL RESULTS

Changes in body temperature, breathing rate and heart contraction rate in the animals during the experiments are presented in Figs. 2, 3, 4 and 5.

Confinement in the hermetically sealed chamber at an ambient temperature of 22° led to a considerable drop in body temperature of the animals. In the helium-oxygen medium this drop took place at a considerably higher speed and was on the average 4.4° greater than in air. Typically, a corresponding drop in body temperature was observed in the air as well as the helium-oxygen media as early as a few minutes after sealing the chamber and continued all the way up until the animal perished.

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At a helium-oxygen temperature of 27° the body temperature of the test animals began to drop immediately after sealing the chamber and at the instant breathing stopped it was 3° lower than in air. At the same time the body temperature in the control experiments for the first 8 minutes after sealing the chamber increased and only subsequently was a gradual drop observed.

At an ambient temperature of 31° in the control experiments a rather prolonged rise in body temperature (up to 23 min) was observed already after sealing the chamber. During the next 9-10 min of the animal's life the body temperature began to drop and toward the instant the rats died it was still 0.6° above the initial level. In the experiments with the helium-oxygen medium we also noted a rise in body temperature of the animals, but, in contrast with the control experiments, the rise was very slight and continued for a total of only the first 13 min after sealing the chamber. The subsequent drop in body temperature was more pronounced and longer and near the instant of death it was on the average 1.0° below the original level.

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At an ambient temperature of 36° the animal temperature rose gradually at approximately the same degree both in air and in the helium-oxygen medium. In this case the body temperature rose continuously until the death of the animals.

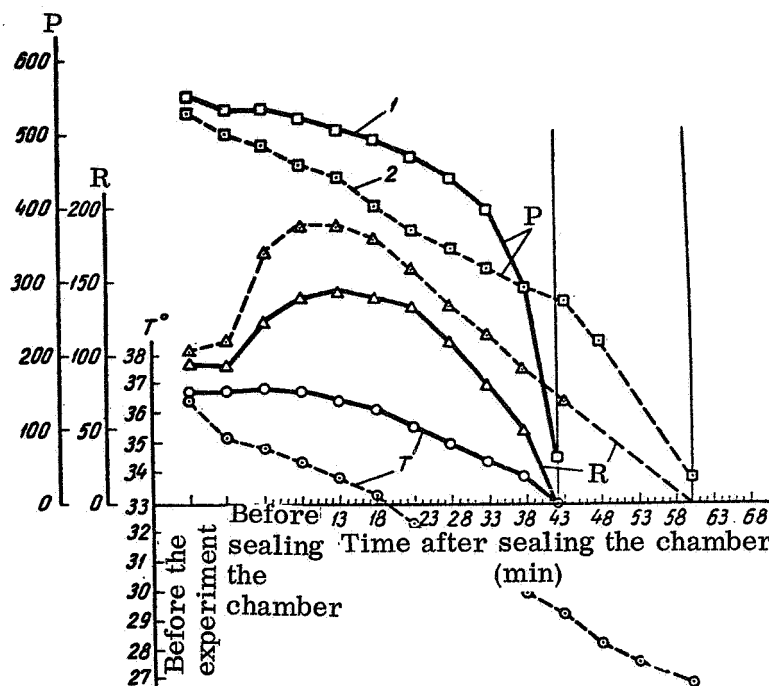


Figure 2. Variations in Pulse Rate (P), Respiration Rate (R) and Body Temperature (T) of the Animals at a Chamber Temperature of 22°:

1 and 2—Air and Helium-Oxygen Environments, Resp.

Confinement of animals in a hermetically sealed chamber also led to a considerable change in the respiratory function. After sealing the chamber the respiration rate of the rats increased in both the air and the helium-oxygen environments. Typically, at all four investigated temperatures of the ambient medium the breathing rate was, as a rule, higher in the helium-oxygen medium experiments than for the corresponding measurements in the control experiments. This showed up particularly evident in the series of experiments at temperatures of 22 and 27°. Thus, e.g., in the eighth minute after sealing the chamber in control experiments the respiration rate rose relative to the original values by 49% at a temperature of 22° and by 30% at 27°, whereas in the helium-oxygen medium the corresponding increase in respiration rate was 71 and 67%. /225

Changes in the heart-contraction rate of rats during confinement in a hermetically sealed chamber was intimately associated with changes in body temperature (Fig. 2-5).

In those cases when the body temperature of the animals dropped, a decrease was also observed in the heart-contraction rate in both the air and the helium-oxygen environments. The pulse rate dropped simultaneously at approximately the same speed as the drop in body temperature. In the helium-oxygen medium at ambient temperatures of 22, 27 and 31° the decrease in heart-contraction rate and the drop in body temperature were more pronounced than in air. /226

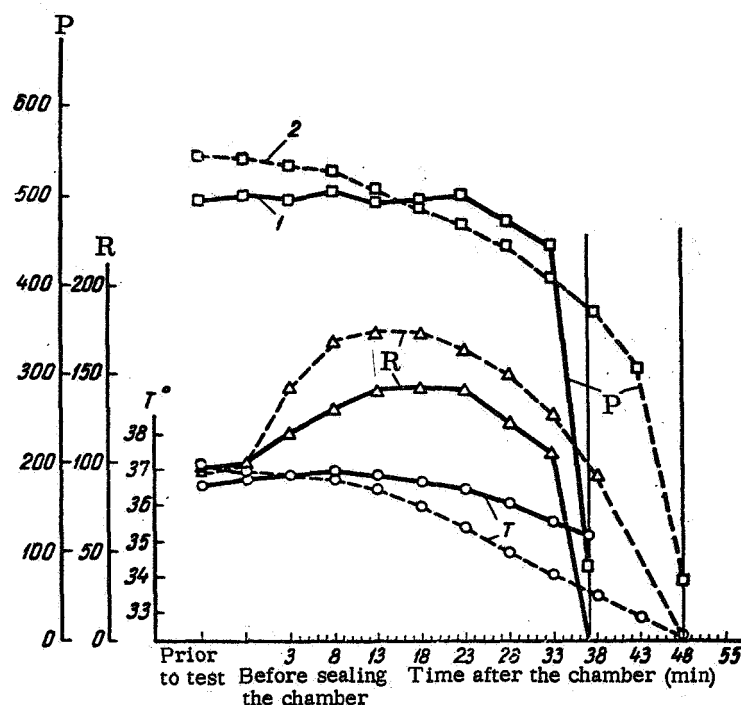


Figure 3. Changes in the Physiological Indices of Animals at a Chamber Temperature of 27°.

Notation the Same as in Fig. 2.

If the body temperature of the rats dropped, a corresponding increase in the heart-contraction rate was also observed. At an ambient temperature of 36° the rats were noted to have an approximately identical rise in body temperature in both the air and helium-oxygen environments. It was precisely in this case that the animals exhibited no essential difference in degree of increase of the heart-contraction rate in the gas media being studied.

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In all the experiments, without exception, cardiac activity was still observed at the instant the animals ceased to breathe. Given below are data on the heart-contraction rate of the rats at the instant respiration stopped at the various gas-environment temperatures:

Gas medium	22°	27°	31°	36°
Air	65	82	116	114
Helium - oxygen . . .	36	69	88	120

As is evident from these data, the heart-contraction frequency of the animals at the instant they stopped breathing was directly proportional to the rise in chamber temperature. At ambient temperatures of 22, 27 and 31° the heart-contraction rate in the helium-oxygen medium was noticeably lower than in air. At 36° no appreciable difference was observed in the pulse of the rats.

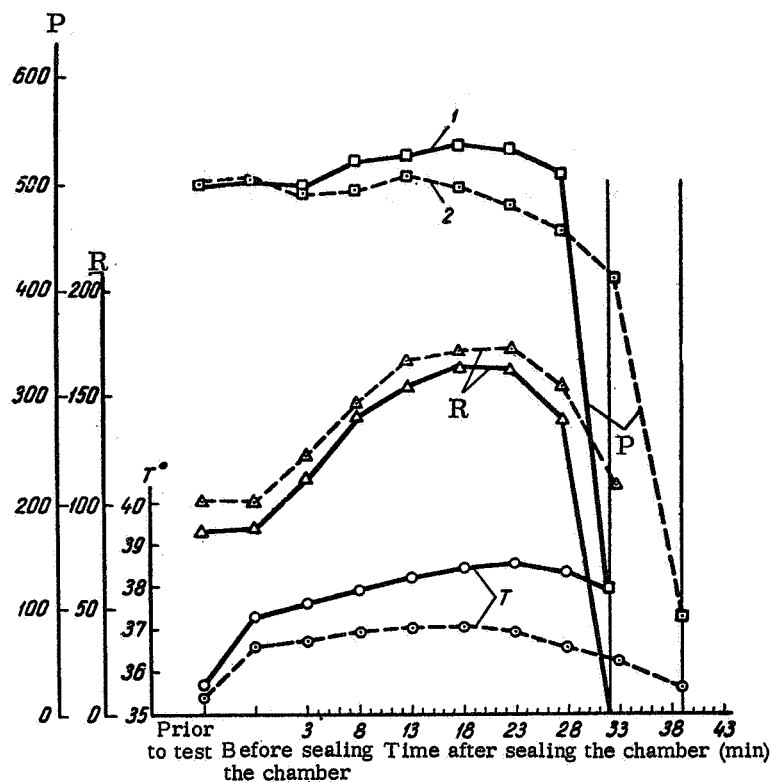


Figure 4. Changes in the Physiological Indices of Animals at a Chamber Temperature of 31°.

Notation as in Fig. 2.

The results of determining the O_2 and CO_2 content (in %) in the chamber atmosphere at the instant of death of the animals are given below:*

Gas medium	O_2	CO_2
Air	7.1	10.5
Helium-Oxygen	6.0	11.4

The data given in the table indicate that in the helium-oxygen medium at a temperature of 22° the animals died at lower oxygen concentrations and higher CO_2 concentrations than in air.

The lifetime of the rats in the helium-oxygen medium at 22° increased as compared with air by 42%. As the chamber temperature was raised, this difference gradually diminished. At 36° no statistically reliable difference was

* The gas composition of the chamber atmosphere at the instant the animals died was studied in the experiments performed at a temperature of 22°.

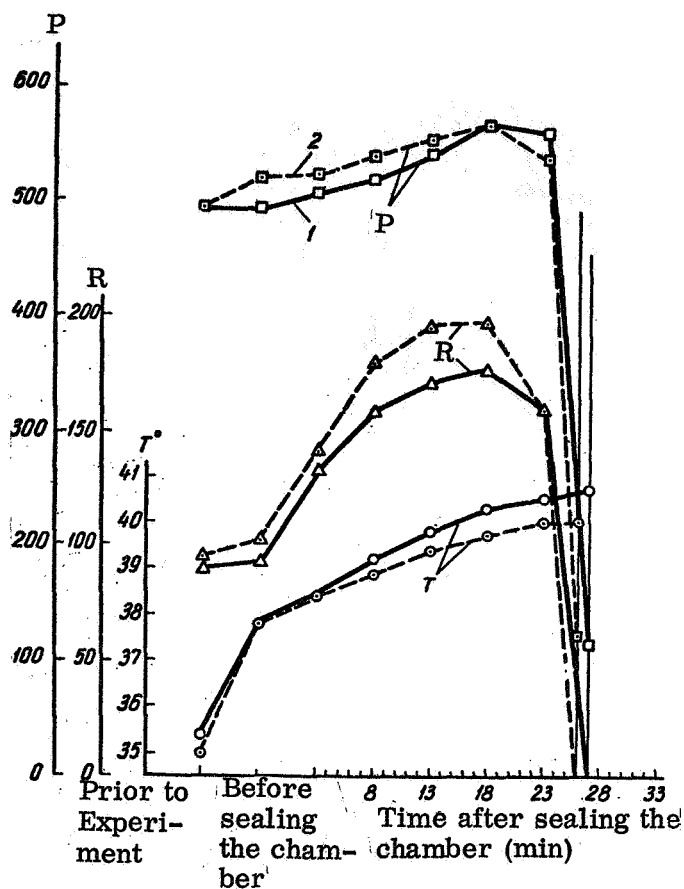


Figure 5. Changes in the Physiological Indices of Animals at a Chamber Temperature of 36°:

Notation as in Fig. 2.

observed in the lifetime of the animals in the helium-oxygen environment and in air (see the table).

Both in air and in the helium-oxygen medium the lifetime of the rats gradually decreased with increase in the ambient temperature. In the helium-oxygen medium, however, this decrease was less pronounced than in air. When the chamber temperature was raised by the same amount (from 22 to 36°) the lifetime of the animals in the control experiments decreased by 54.5%, whereas in the helium-oxygen medium this amount was 128.6%.

DISCUSSION OF THE EXPERIMENTAL RESULTS

/2:

Among the experimental data we obtained of greatest interest is the considerable increase in lifetime of the animals in a hermetically sealed chamber in which the atmospheric nitrogen was replaced by helium at a temperature of 22°. The available literature contains no information on the effect of a helium-oxygen medium on animals confined in a closed volume. Therefore

it is possible to make a judgement as to the reasons for the indicated increase in lifetime only on the basis of an analysis of the functional changes observed in animals in the course of the experiments we conducted.

Lifetime (min) of Rats in a Hermetically Sealed Chamber at Various Ambient Temperatures

Gas medium	22°	27°	31°	36°
Air	42.2±1.2	37.0±1.1	32.4±0.9	27.3±0.7
Helium-oxygen	59.9±3.5	43.2±2.7	39.1±1.4	26.2±0.9
Changes of lifetime in He-O ₂				
as compared with air (%) .	+42.2*	+30.3	+20.7	-3.7
Difference probability (P)†	<0.001	<0.01	=0.001	>0.2

*The plus sign denotes the corresponding increase and the minus sign the decrease of lifetime in the helium-oxygen medium.

The most essential factor in explaining the increase in lifetime of the rats in a helium-oxygen environment is the variation in body temperature. In our experiments it was demonstrated that confinement in a hermetically sealed chamber without atmospheric regeneration at an ambient temperature of 22° led to a considerable drop in body temperature of the animals both in the air and in the helium-oxygen media. The analogous fact of a drop in body temperature of mice (by 3.9° while confined in a closed air atmosphere at an ambient temperature of 20°) as noted in [10].

The main active factors in the confinement of animals in hermetically sealed chambers are the decrease in oxygen content and the increase in CO₂ concentration in the inhaled air. Each of these factors exerts a specific effect on the heat regulation of the organism.

It was found that oxygen deficiency in the inspired air leads to a drop in body temperature of animals even at ordinary room temperature [1, 3, 4, 9, 13, 15]. This occurs as a result of depression of such heat-production mechanisms as muscular tremor and thermoregulatory muscular tonus [5, 8]. A reduction of body temperature under the conditions of oxygen deficiency may be considered as a defensive reaction of the organism, since the oxygen consumption of the animals decreased at the same time [13]. On the basis of his investigations, L. L. Shik arrived at the conclusion that a decrease in oxygen intake during hypoxia is a primary process, as a result of which hypothermia develops (due to a drop in heat production). Thus, a drop of body temperature under the conditions of oxygen starvation is an external symptom of a decrease in intensity of oxidizing processes in the organism and of oxygen intake.

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Increased concentrations of CO₂ in the inspired air also exert a depressive effect on heat-production mechanisms, leading to a drop in body temperature [2, 12, 16]. In the case of increased CO₂ concentrations the body temperature decreases not only as a result of a decrease in oxygen intake and heat production of the organism.

Under the combined influence of oxygen deficiency and increased CO₂ concentrations the depressing effect of these two factors on heat regulation is summed, leading to a stronger drop in the body temperature of animals [14, 15]. These are the basic reasons for disruption of heat-regulation mechanisms and for a decrease in body temperature when animals are exposed to an ordinary air environment in hermetically sealed chambers.

In case nitrogen is replaced by helium in the atmosphere of hermetically sealed chambers, the effect of the two factors mentioned above is augmented by the effect of the higher cooling properties of the helium-oxygen medium [7]. When there is an oxygen deficiency and CO₂ concentrations are high, this effect is especially intense, since it appears against a background of depressed heat-production mechanisms and increased heat transfer. This situation is confirmed by the experimental data obtained at an ambient temperature of [22]. In the helium-oxygen medium the body temperature of the animals dropped 4.4° lower than in air.

The higher cooling effect of the helium-oxygen medium can be compared with the effect of a drop in air temperature in hermetically sealed chambers. It was shown in [10, 15] that a decrease in the temperature of the air environment leads to a lower drop in body temperature and to longer lifetime of animals in a closed volume. The reason for this is the sharper decrease in oxygen intake by the animals.

By comparing our experimental data with the results of the investigations of V. A. Konstantinov [10], it is easy to see that in both cases the lifetime of the animals increased as a result of a lower drop in body temperature. The difference consists only in the fact that in the helium-oxygen medium the more pronounced cooling of the animals was governed by the high thermal conductivity of the helium, while in Konstantinov's experiments it was governed by a decrease in temperature of the ambient air.

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On the basis of the data we examined it is possible to reach the conclusion that the increase in the lifetime of animals occurred as a result of a more pronounced drop in the level of the exchange processes and of the oxygen intake than in air. An external indication of this fact was the lower drop in body temperature of the animals.

In Konstantinov's work [10] it is said that a decrease in air temperature increases the lifetime of animals in a closed volume not only because of a sharper decrease in oxygen intake, but also because of a decrease of sensitivity of the animals to oxygen starvation. In his experiments the mice died at an air temperature of 5° under a lower oxygen content and higher CO₂ concentrations than at a temperature of 18-20°.

In the experiments we performed at 22°, death of the rats in the helium-oxygen medium set in at lower oxygen concentrations and higher CO₂ concentrations than in air. This is evidence of a decrease in sensitivity of the animals to oxygen starvation in the helium-oxygen medium at a temperature of 22°.

The assertion that the increased cooling effect of the helium-oxygen medium is the main reason for an increase in lifetime of the animals at a temperature of 22° is supported by experimental data obtained at other ambient temperatures. In the experiments it was established that the prolongation of the life of the animals in the helium-oxygen medium, as compared with air, gradually decreases as the chamber temperature is raised to 27 and 31°. At 36° no statistically reliable difference in the lifetime of animals was observed. As the difference in lifetime of the rats in the helium-oxygen medium and air decreased, so did the difference in body temperature. If at 22° the body temperature of the animals dropped around the time of their death in the helium-oxygen medium 4.4° lower than in air, at 27 and 31° this value decreased, amounting respectively to 3.0 and 1.6°. At 36° the body temperature in the rats no longer differed in the helium-oxygen medium and in air, rising by approximately the same amount toward the end of the experiments.

The gradual decrease in difference of the body temperature of animals in the helium-oxygen medium and air as the chamber temperature increases leads to

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the final conclusion that the increased cooling effect of the helium-oxygen medium is the reason for the observed changes. As was pointed out in the preceding paper, the cooling effect of the helium-oxygen on the organism also decreases with increasing ambient temperature [7]. This occurs because of the decrease in heat transfer from the organism by conduction.

As is well known, heat transfer by conduction, besides heat conductivity of gas, depends also on a difference between body temperature and the temperature of the ambient gaseous medium. In the experiments a chamber temperature rise to 27, and especially to 31° narrowed this difference and led to a reduction of heat transfer from the animals both in the air and the helium-oxygen environments. In the helium-oxygen medium, however, heat transfer by conduction was nonetheless, considerably greater than in air as a result of the high heat-conductivity of helium. It is precisely this factor that explains the drop in body temperature of the mice in the helium-oxygen medium at 31°, whereas in air an increase in body temperature was observed at the same time. In the experiments conducted at 36°, no essential difference was noted in the lifetime and body temperature of the animals in the helium-oxygen medium and in air. This is due to the fact that the body temperature and that of the ambient medium were practically equal, and therefore this is due also to the absence of conductive heat release either in the air or the helium-oxygen environments. Therefore, regardless of the high heat-conductivity of helium, heat exchange of the animals at the given ambient temperature did not differ substantially in the helium-oxygen medium and in air.

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SOME PECULIARITIES OF THE SPEECH FUNCTION IN A CHANGED GAS MEDIUM

V. S. Kuznetsov

In recent years the interest of researchers has increased in the study of the effect on the human and animal organism of a helium-oxygen mixture obtained by replacing atmospheric nitrogen by helium [1-3]. The substitution of helium for nitrogen has a very strong effect on the character of speech [2].

In the available literature a relatively small number of papers [5, 6], has been devoted to the problem of studying the function of speech during the respiration of special gas mixtures. In 1962 there appeared the paper of R. Beil [9], which was devoted to the study of the frequency spectrum of vowels of the English spoken language pronounced while breathing a helium-oxygen (HeO) mixture. Spectral analysis of the recorded speech showed that the frequency of the fundamental changed but little in the HeO medium, while the frequency of the first, second and third formants of all vowels increase at a ratio dependent on the composition of the gas medium.

In our experiments (I. Ya. Borshchevskiy and V. S. Kuznetsov), the peculiarities of speech formation while breathing an HeO mixture were studied in the course of two long experiments, of a total duration of 22 and 30 days, in which two test subjects participated. In contrast with the work of non-Soviet authors, the test subjects not only breathed, but were also continuously confined in the HeO atmosphere for 10 and 25 days. The principal measurements were made in the morning hours, every two days during the experiment; control experiments in a normal atmosphere were performed 1 and 3 days prior to the beginning of the experiment and after its conclusion.

During the experiment we studied the following characteristics of the speech function:

- 1) the features of the frequency composition of speech from the results of a spectral analyzer of the vowels of Russian spoken language a, o, i, y, u, e, both in the syllables da, do, di, my, ekh, and in the "standard phrase" paz, dva, tri;
- 2) the quality of speech formation, from articulation data, while reading lists of words;
- 3) the dynamics of the amplitude characteristics of speech.

The "standard phrase" used prior to the research is not generally accepted and does not reflect a statistical distribution of the sounds of Russian speech, but because of its simplicity it is widely used in special investigations.

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The "standard phrase" was pronounced by the test subjects in one breath 5-6 times, and varied sounds were kept standard for 1.5-3 sec. In pronouncing

the sounds the test subjects made use of three pickups: an MD-55 electromagnetic microphone having a comparatively even frequency characteristic; a DEMSh-1A noiseproof differential microphone, whose frequency characteristic has a rise of 6 db/octave from 300 to 1,000 Hz; and an LA-5 throat microphone. In order to determine the effect of aural self-monitoring on the quality of articulation in an HeO medium, in some cases the ears of the test subjects were covered by mufflers with earphones, through which white noise or music was transmitted. Some word lists were read by the test subjects at a whisper. The microphones and throat microphone were located together with the test subjects within the object in which the artificial atmosphere was created. The speech of the test subjects was recorded on a tape recorder having a smooth frequency characteristic of reproduction of ± 3 db.

The word lists were received by a team of trained auditors and the percentage of correctly received words was determined. Spectral analysis of the "standard phrase" and of the vowels was made by means of a spectreanalyzer with 1/3-octave filters; for this purpose a roll of electromagnetic tape with a record of the standard phrase or of the vowel being investigated was spliced together. The roll was played on a tape recorder; from the output of the recorder the voltage was transmitted to the input of the spectral analyzer. The automatic switching rate of the filters was chosen so as to transmit the signal from the roll twice into one filter. In analyzing the vowels we determined the magnitude of the peak voltage developed by the signal of each sound in the 1/3-octave filter.

In the two experiments a total of 95 lists of 25 words each were subjected to articulation studies. Of these, 61 lists were read while breathing the HeO mixture and 34 under ordinary conditions. Each of the 6 vowels used were pronounced by the test subjects 100 times, and of these, 75 times in the HeO medium.

EXPERIMENTAL RESULTS

As is well known, a speech wave is characterized by a specific spectral shape whose resonant peaks are known as formants. The most intense harmonic components of the acoustic oscillations are concentrated in the formant regions. The classical theory of speech formation ascribes to each voiced sound a particular place for its formants in the frequency scale, making it possible to identify the different vowels [6]. Spectral analysis of the sounds by means of the 1/3-octave filters cannot completely replace exact formant analysis, due to the comparatively large width of the filters. But the location of the formants can be estimated with good accuracy from the maxima in the spectral pattern. Given in the figure are examples of such a type of analysis of the vowels *a*, *o*, *u*, pronounced by the test subjects under ordinary conditions and in the HeO medium through the linear channel. In the spectrograms the intensity of the spectral components is plotted along the vertical in relative units (db); along the horizontal are the mean frequencies of the filters. From the figure it is evident that the first formant in the vowel *a* is located in the region of 600-800 Hz under ordinary speech-formation conditions, whereas it is shifted to the region of 800-1200 Hz in the HeO medium. The second formant is shifted from the 1000-Hz region to 2000 Hz, and the third from 2500 Hz to the region of 4000-5000 Hz. At the same time the intensity level of the third formant is considerably reduced (by 15 db). The frequency of the energy maximum of the vowel *o* increases by a

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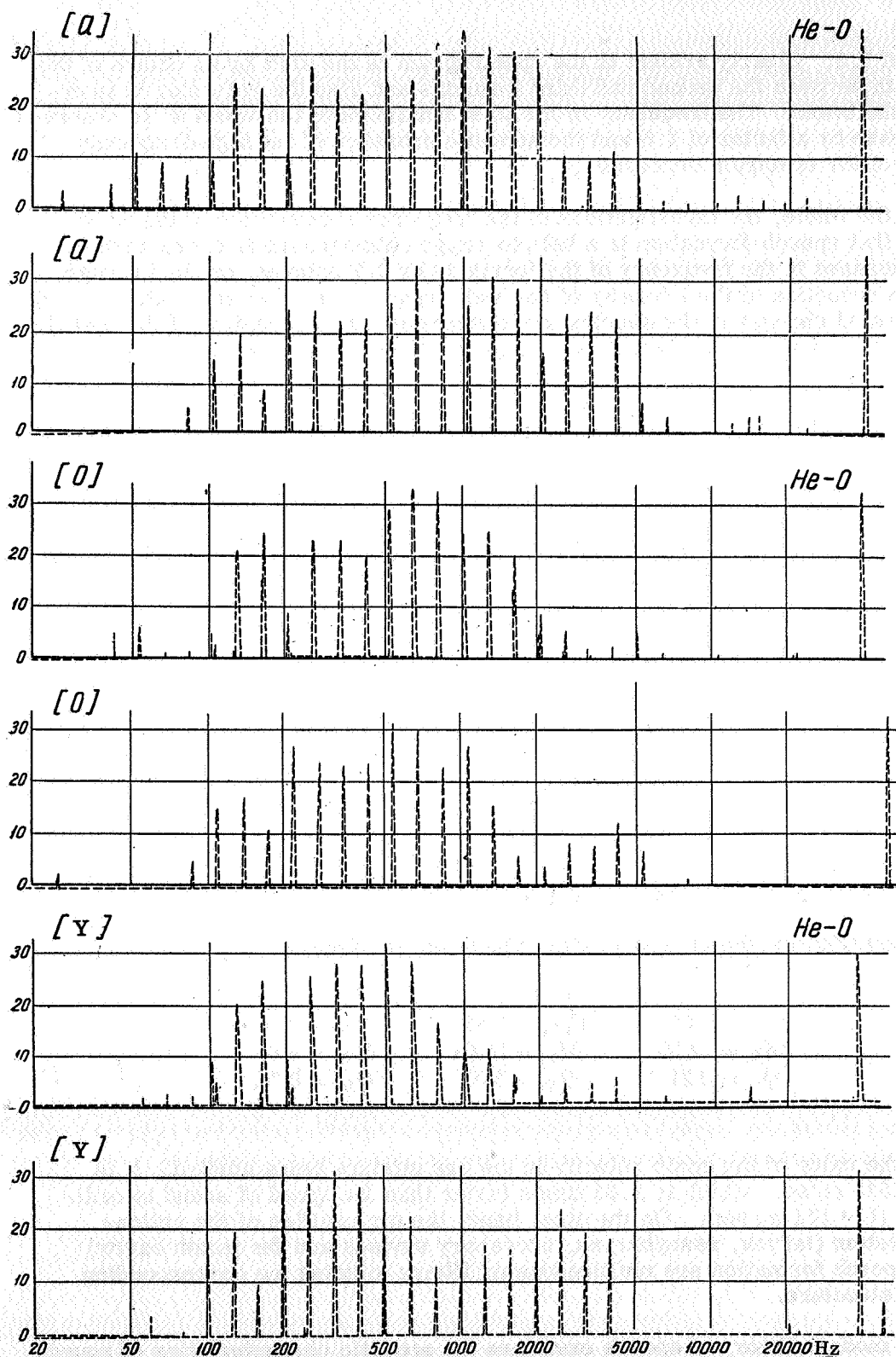


Figure 1. Example of Spectral Analysis of the Vowels a, o, y, Pronounced in a Helium-Oxygen (HeO) Atmosphere and in Normal Air.

factor of 1.3. Clearly evident in the spectrogram is the shift by an octave of the minimum between the second and third formants and also the reduction in intensity of the latter. The frequency of the first maximum of the vowel *u* is observed to increase by a factor of 1.5 and the acoustic pressure of the high-frequency portion of the spectrum decreases.

On the whole, the investigations of the frequency composition of the vowels showed that speech-formation in a helium-oxygen atmosphere is characterized by an increase in the frequency of the formants by 0.7 octaves, on the average, and by a reduction of the intensity of the high-frequency components. Subjectively, the indicated changes in the spectra are interpreted as a disruption of the melodic pattern of the voice, which takes on a "squeaky" character with shades of "nasality."

The increase of the formant frequencies of the vowels in the HeO atmosphere can be explained by the physical features of this gas mixture, in particular by the speed of propagation of the acoustic oscillations in the mixture and by the functional nature of the articulatory system. The artificial gas mixture used in the experiments contained 21% oxygen, 2-4% nitrogen and up to 75% helium. The rate of sound propagation in the gas mixture can be determined by the following formula:

$$C = \sqrt{\frac{RT^0 \left(\sum_i Q_i C_{Vi} + R \right)}{\sum_i M_i Q_i \sum_i Q_i C_{Vi}}},$$

where Q_i are the molar fractions of the different components (for ideal gases they coincide with the volumetric ratios); M_i , C_{Vi} are the molecular weights and the heat capacities of the respective components; R is a gas constant, equal to 1.987 cal/deg x mole or 8.314×10^7 erg x deg /mole [4].

By substituting the corresponding values into the formula:

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$C_{VO_2} = 4.96$	$C_{VN_2} = 4.94$	$C_{VHe} = 3.00$
$M_{O_2} = 32.00$	$M_{N_2} = 28.01$	$M_{He} = 4.00$
$Q_{O_2} = 0.21$	$Q_{N_2} = 0.04$	$Q_{He} = 0.75,$

we find the value of the sonic velocity in the gas mixture being studied. It is equal to 540 m/sec, which is 1.63 times faster than the speed of sound in ordinary air ($C = 331$ m/sec). On the other hand, the air cavities of the articulatory system (larynx, nasopharynx, accessory sinuses and the mouth cavity) during speech formation are multiresonator filters forming the corresponding formant structure.

The modern theory of speech examines the acoustic characteristics of sounds in the form of a product of the function (S), which represents modulation of the

air stream by the vocal chords, and of the filtering function of the vocal tract (T) [7]. The investigations of R. Beil show that the fundamental frequency of the voice, i. e., the oscillation frequency of the air stream does not change when breathing on HeO mixture. Consequently, the replacement of nitrogen by helium has no effect whatever on the functioning of the vocal chords. On the contrary, the function T, which is equivalent to several coupled resonators, may change considerably when the speed of propagation of sound increases. According to [9], the frequency of each formant is determined by the ratio of the sonic velocity to twice the length (l_n) of the corresponding equivalent resonator, i. e., $f_n =$

$C/2 l_n$. On the basis of this fact, it can be assumed that when the articulatory cavities are filled with an HeO mixture, the frequency of the formants increase, as compared with air, proportionally as the sonic velocity in the HeO medium exceeds the sonic velocity in air, i. e., by a factor of 1.63 in the case being considered, corresponding to a shift of 0.8 octaves toward the higher frequencies. Generalizing these conclusions, it can be said that speed formation in different gas mixtures is characterized by a shift in the location of the formants on the frequency scale, the shift being dependent on the ratio of the sonic velocity in the new medium to that in air. Frequency analysis of vowels in an HeO mixture has shown sufficiently good agreement of this conclusion with actual results. Without doubt, filling a resonator with the HeO mixture leads to a change of the entire transfer function of the speech tract; this, in particular, causes a reduction in the intensity of the high-frequency components of the spectrum. We did not make a special quantitative analysis of this phenomenon.

In studying the amplitude levels of speed it was found that a certain reduction in speech intensity (on the average 5 db) is observed immediately upon the transition to breathing the HeO mixture. On the second day of confinement of the test subject in the artificial atmosphere, the speech level increased almost to the original level owing to compensatory reactions and to aural self-control. Elimination of self-auditing by transmitting white noise and music to the earphones did not lead to a reduction in speech intensity or to a sharp deterioration of articulation (see the table). Sounds pronounced by the test subjects in the HeO medium are not only well identified, but also transmit certain personal traits of the speaker which are defined, as we know, by the fine structure of the spectrum. This is also confirmed by the articulatory changes. From the table it follows that the percentage of speech recognition when breathing the HeO mixture is close to 100. Especially fine are the results using the MD-55 and DEMS-1A microphones; somewhat worse is articulation using the laryngophone.

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It is necessary to emphasize, however, that the high percentage of recognition obtained in our experiments is explained by the good transmission conditions, by the high redundancy of the Russian language, and is supported by the considerable force of the aural and vocal compensation mechanisms. A proof of this may be the sharp reduction in speech recognition when reading word lists at a whisper (see the table). Elimination of the voice from the speech-forming process leads to a decrease in recognition from 95 to 50%. It must be assumed that in actual space flight the use of a helium-oxygen mixture may result in considerable deterioration of the communication quality in the presence of noise during transmission and reception if various speech correction measures are not provided for.

Recognizability of Speech (in %) From the Data of
Articulatory Measurements

Microphones	Air medium, days of test		Helium-oxygen medium, days of the test					
	1-st	2-nd	3-rd	5-th	9-th	18-th	24-th	29-th
MD-55	100	100	100	100	95	95	100	100
DEMSH-1A	95	100	100	100	100	100	100	100
LA-5	85	85	70	70	90	80	55	80
MD-55, whispering ..	95	95	50	50				
DEMSH-1A whispering	95	100	60	60				
MD-55 transmission . of white noise into the earphones	100	100	95	95	95	90		

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RESPIRATION OF OXYGEN AT HIGH PRESSURE, FEATURES OF AND TRAINING FOR SUCH RESPIRATION AND THE PHYSIOLOGICAL BASIS

V. A. Skrypin

In a preceding article [4] we showed that the so-called reserve time of man at high altitudes is so small that it does not answer the safety requirements for high-altitude and space flight. According to our data, if the oxygen supply is cut off, the reserve time of a pilot and astronaut at an altitude of 9000 m is numbered in minutes, and in seconds beginning at an altitude of 10,000 m. As our investigations in a pressure chamber have demonstrated, when a spacecraft cabin is depressurized at altitudes greater than 13,000 m, the crew is in danger of quick loss of consciousness, regardless whether pure oxygen is being breathed or not. The reason for loss of consciousness under such conditions is the abrupt drop in partial oxygen pressure in the inhaled and alveolar air and blood deoxygenation, typical for such altitudes, i. e., losses in oxygen reserves through the lungs.

The results of a study of the problem of the reserve time of a human being in the entire range of flight altitudes and especially the strikingly small values at high altitudes were the reason for further search for effective ways and means which might substantially increase the reserve time of a pilot and astronaut in an emergency situation at high altitudes.

The positive role of carbon dioxide in preventive treatment of oxygen deficiency has been widely emphasized in the literature, and suggestions have been made that the respiration of carbogene may considerably strengthen the high-altitude stability of the human organism to oxygen deficiency at high altitudes [2-8, 12]. It was demonstrated by us experimentally that when breathing carbogene at altitudes of 13,500 m and above no increase in reserve time is achieved; in fact, deterioration was observed in a number of cases as compared with the respiration of pure oxygen.

The basic reason for the loss in human efficiency and for the sharp deterioration of his general state and well-being when breathing carbogene *was the onset of acute oxygen deficiency, which represented a direct threat to his life [5].

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It has become obvious that it is possible to maintain satisfactory efficiency of a pilot and astronaut and to prevent loss of consciousness when the cabin is depressurized at great altitudes only by ensuring a sufficient oxygen supply for the human organism in such an emergency situation.

In this connection the idea has arisen of supplying oxygen to the respiratory tracts of man under increased pressure.

*Translator's Note: Oxygen with admixture of CO₂.

Tests of the new method of breathing and of test samples of oxygen devices have yielded encouraging results. Despite fixed preconceived views, it has been found that it is possible to breathe for sometime when there is considerable resistance to expiration [11].

Tests of this method of breathing have shown that an increase of 15-25 mm Hg oxygen pressure raises the ceiling for a pilot. At such values of pressure, altitudes of 15,200 m can be reached and maintained for 3-5 minutes.

Pilots using this method of breathing have given positive reports and have remarked that they are less fatigued than when they had to use oxygen equipment of the usual type.

The new method of breathing has proved to be a highly effective measure in raising the oxygen supply of the organism at high altitudes.

In the opinion of other authors the factors limiting the application of respiration at increased pressure may be negative psychological moments (fear) and disruption of the blood circulation. Judging from our experiment, however, the training program we introduced for breathing at increased pressure leads to the development of adaptation by the organism to the unusual breathing and to restructuring of the respiration process: unpleasant subjective sensations are considerably weakened or disappear entirely. Insofar as circulatory disorders are concerned, the use of excess pressure of 2032 mm Hg at altitudes of up to 13,706 m do not cause noticeable derangements of blood circulation.

When the excess oxygen and the altitude of climb are further increased, serious disruptions in blood circulation may appear, going so far as collapse or fainting. Although the contingent of flying personnel and astronauts is selected from among candidates distinguished by a superior cardiovascular system, it is not permissible to fail to allow for the possibility of serious disorders in blood circulation at high excess pressures at maximum altitudes. In fact it can be easily imagined that one-sided increase of the excess pressure in the closed system of oxygen equipment and lungs may lead to a considerable increase in the intrapulmonic and intrathoracic pressure. The major venous channels may be contracted: the suction action of the thorax during inspiration may become sharply attenuated. If the cardiac muscle is relatively weak, the return of blood to the right ventricle may decrease, resulting in a reduction of the blood volume per minute and per beat, thus sharply changing the well-being and the general status of the test subject for the worse. Judging by our data as well as by those of other authors, such cases occur comparatively infrequently, since it has been found that when breathing at increased pressure the blood pressure also increases, although to a lesser extent as compared with that of the excess oxygen pressure used in the space beneath the mask [11]. It is urgently recommended that high-pressure respiration be combined with the use of external compensatory equipment in the form of a special high-altitude compensation suit [9, 10].

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Application of the new method of breathing oxygen at increased pressure is accomplished in two ways. In the first way the excess oxygen pressure in the closed system is maintained constant during the entire respiratory cycle; the intrapulmonic pressure is kept continuously at a higher level as compared with the ambient atmospheric pressure. In the other method, respiration is accom-

plished with variable pressure at various phases of the respiratory cycle. The excess oxygen pressure is produced only in the inspiration phase, and expiration is accomplished either freely, when the excess pressure is completely ejected, or during expiration and the respiratory pause only a part of the excess pressure is ejected to reduce the resistance to respiration at the most difficult moment—in the expiration phase. At the present time it is still difficult to say which of these two methods of breathing oxygen under increased pressure should be preferred.

In our opinion, respiration of oxygen under continuous constant pressure has a considerable advantage over respiration under variable, non-constant pressure.

When breathing oxygen under increased constant pressure, it is easier to keep the partial oxygen pressure in the expired and alveolar air at a stable and necessary level; which is the main purpose for breathing oxygen at increased pressure. Moreover, the organism adapts more readily to constant, invariable conditions. Pressure constancy in a closed system eliminates the unpleasant subjective sensations of labored respiration which exists in man when the upper respiratory tracts are irritated by pressure fluctuations.

A major drawback of breathing oxygen at increased constant pressure is the unrelieved stress on the respiratory musculature, particularly on the muscular apparatus of inspiration, which remains in a state of continuous tonic contraction. / 240 This continuous static work of the respiratory musculature causes constant human stress and strain in breathing oxygen under increased pressure and rapidly leads to depression of respiration and general fatigue. In the opinion of some authors, the rapid onset of fatigue during static work is due to the prolonged and continuous process of excitation in the central nervous system as a result of the continuous flux of afferent pulses from the working muscles, as well as being due to difficulties of blood circulation in the muscles. All this leads to a restriction of the oxygen supply to the muscles and to accumulation of exchange products.

From our viewpoint, it is doubtful whether it should be considered expedient to put the oxygen under pressure only during the inspiration phase with the desire of eliminating labored resistance to expiration. An essential drawback to this method of respiration with alternating pressure is primarily that application of increased pressure during the expiration phase and the respiratory pause negates the advantage of breathing oxygen at increased pressure, because during the expiration phase and the respiratory pause the blood again is saturated when the oxygen pressure in the alveolar air is equal to the pressure of the ambient atmosphere. Consequently, this method of breathing cannot guarantee a constant level of partial oxygen pressure in the alveolar air.

The suggestion that the amount of excess oxygen pressure be considerably increased during the inspiration phase so as to raise the mean partial oxygen pressure in the alveolar air cannot be adopted, since hyperventilation of the lungs, which would occur in this case, may lead to substantial erosion of CO_2 and, consequently, to a dangerous degree of hypocapnia.

Of considerable interest is the respiration of oxygen at increased pressure not with complete interruption of pressure in the expiration phase, but only during some portion of it, which would have to be determined experimentally.

All researchers into the problem of breathing oxygen under increased pressure know quite well that even in this case, when we apply respiration of oxygen at constant pressure, it is impossible to prevent the excess oxygen pressure in the space under the mask, and therefore in the lungs, from dropping during the inspiration phase, when the chest cavity expands. On the other hand, during expiration it increases. Consequently, there are slight fluctuations in excess oxygen pressure even when breathing under constant pressure. They depend on variations in the capacity of the chest cavity during the in- and expiration phases.

Taking the constant stress and strain of the human being into account, due to static strain on the basic and auxiliary respiratory musculature while breathing oxygen under constant high pressure, aggravated by the static strain on the skeletal musculature due to the tightening and continuous compressing high-altitude compensation suit, it is necessary to think about reducing the constant stress and strain on the pilot by allotting him brief periods of rest during the individual phases of the respiration cycle. Such short-term periods of rest during the individual respiratory phases can be achieved by partial interruption of the excess oxygen pressure in the space under the mask as well as in the chambers of the tightening device of the high-altitude compensation suit. The magnitude of such partial interruption of the excess oxygen pressure in the mask space and in the chambers of the tightening device must not exceed the value at which acute hypoxia or hypocapnia may arise. It must be completely sufficient to remove, completely or partially, the stress and strain on the pilot during these rest periods.

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With such variable pressure and partial interruption of the oxygen pressure under the mask and in the chambers of the tightening device of the high-altitude suit, it is possible to reduce the stress and the overall strain, which sharply limit the time of exposure of a pilot and astronaut at high altitudes when breathing oxygen under increased pressure. In this case we can hope for an improvement in the supply of blood to the respiratory and skeletal musculature and for attenuation of the flux of afferent signals into the central nervous system, and therefore for better altitude endurance and longer exposure time for pilots and astronauts when breathing oxygen with alternating increased pressure.

Such, in general outlines, are the purpose, approaches and methods of applying oxygen respiration under increased pressure in aviation and astronautics. In the experiments we conducted, the use of the new method of breathing oxygen under very high pressure increased the reserve time of a human being by several factors in an emergency situation at altitudes of more than 13,000 m and gave him the capability of emergency descent with an airplane to a safe altitude. It must be immediately emphasized, however, that positive results can be realized with the new breathing method only when the process of learning the unusual and difficult method of breathing with appreciable resistance to expiration is correctly organized, when the techniques and rules of use of the oxygen equipment are thoroughly known, when the special high-altitude gear is correctly chosen and thoroughly adjusted, and when the flying personnel is given rational preparatory training in breathing oxygen under increased pressure.

Teaching and training flying personnel and astronauts to breathe oxygen under increased pressure are the most important of the conditions enumerated above.

There are various opinions on the problem at hand. The aim of the present paper is to examine, in the light of aviation and space medicine, the physiological prerequisites that must be taken into account in developing a rational schedule for training flying personnel and astronauts to breathe oxygen under increased pressure. /242

Respiration of oxygen under increased pressure when there is considerable resistance to expiration is at first unpleasant and is painfully endured by a human being, especially when the uncompensated excess pressure is at maximum values (25-30 mm Hg). But repeated systematic training leads to development of adaptation to this method. In each of our test subjects we observed the process of adaptation of the organism to respiration of oxygen under increased pressure, in the form of a number of high-altitude exercises with gradual increase in the magnitude of the excess oxygen pressure under the mask and in the altitude of climb in each successive exercise. Our suggestion concerning the expediency and necessity of introducing preparatory training for respiration of oxygen under increased pressure was based on the fact, widely known in the field of physiology, that the repeated systematic action of any stimulus leads to the evolution of adaptation, resulting in the appearance and development of new coordinational relationships in the central nervous system and its higher organs and, in the final account, attenuating the action of the stimulus. Sometimes the organism ceases to react to the stimulus altogether.

On the other hand, we know that the cerebral cortex has direct effects on the processes of respiration and blood circulation.

When breathing under increased pressure, strong unusual fluxes of afferent pulses are transmitted to the central nervous system as a result of stimulation of the receptors of the respiratory and cardiovascular systems as well as of the respiratory musculature and organs of the bust cavity. It has been found that these pulses inhibit respiration by reflex, leading to a reduction in blood pressure and to damping of the cardiac activity.

Respiration under increased pressure leads to functional disorders in the respiration and blood-circulation processes which are proportional to the magnitude of the excess oxygen pressure in the space under the mask. The maximum value of the excess (uncompensated) pressure that can be endured by the human organism is 25 mm Hg. Even in this case, however, the act of respiration and the process of blood circulation are not immediately normalized, but only gradually during the process of adaptation of the organism as a result of restructuring of the coordinational relations in the central nervous system often a number of repeated exercises, increasing in difficulty, while breathing oxygen under increased pressure. The magnitude of the uncompensated excess pressure of 30 mm Hg represents a limit on the compensatory capabilities and is no longer endurable by the human organism, either with high-altitude or ground exercises, while breathing oxygen under increased pressure (A. P. Apollonov, M. I. Vakar, P. K. Isakov, et al.). /243

On the other hand, the investigations we made in 1950 on the partial pressure of gases in the alveolar air when breathing oxygen under increased pressure revealed a considerable decrease in the partial O_2 and CO_2 pressure, especially at those altitudes which are the limit of application of oxygen equipment with excess pressure. The partial oxygen pressure in alveolar air at an altitude of 15,000 m (using an oxygen system of the KP-28 type) fluctuated within the limits of 37-48 mm Hg and came close to its critical level (about 30 mm Hg), which is the hypoxia limit that is unendurable to the human organism. The partial CO_2 pressure at the same altitude fluctuated in the range 20-26 mm Hg, which also comes close to the critical hypocapnia limit.

Our studies revealed the dangerous effect of hypoxia and hypocapnia whenever the partial oxygen pressure in alveolar air dropped below the limits of 40 mm Hg and the partial CO_2 pressure below 20 mm Hg while untrained personnel breathed oxygen under increased pressure.

Thus, when breathing oxygen under increased pressure, the human organism is subjected to the complex effect of strong and unusual stimuli. Among these the most important are the excess pressure itself, hypoxia and hypocapnia. All these factors, or each of them separately, when they reach an extraordinary level, may become the leading factor in the negative effect of altitude on the human organism. It is obvious that either of the three, excess pressure, hypoxia or hypocapnia, may play a negative part in the genesis of functional disruptions of the organism at high altitudes, the negative effect being aggravated when all three exert a simultaneous effect on the organism.

Of major importance in the complex effect is apparently the factor which, under given concrete conditions, first reaches the level at which it is critical for the organism. Besides the major active factors we cannot underrate the significance of the effect of the very factor of air rarefaction and of the resultant effects, namely, decompression phenomena, tension of the nervous-psychic type during tests in a pressure chamber or in high-altitude flight, and the appreciable static muscular work involved in using sets of oxygen equipment while tightly laced up in a high-altitude suit. All this complicates pilot activity and aggravates the effect of the major active factors on the human organism while breathing oxygen under increased pressure.

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A negative psychological outlook and the volitional qualities of the examinee, who may or may not be capable of suppressing the adverse moments (fear, lack of confidence in the equipment, in oneself, uncertainty of one's capabilities, etc.), are of considerable significance, especially during the first exercises and climb operations while breathing oxygen at high pressures. This negative aspect may be the reason not only for changes in the activity of a number of organs and systems, but may also cause or aggravate the evolution and duration of a number of adverse, purely vegetative reactions, leading to deterioration in the well-being and overall state of the test subjects' organism while breathing oxygen at increased pressure (retardation of pulse rate, paleness, cold sweat, collapse, incipient fainting state or fainting state). Consequently, a negative psychological outlook may in itself be the only reason for failure to endure altitude and respiration under high pressure.

This brief examination of all the physical, physiological and psychic factors of oxygen respiration at high pressure was intended to demonstrate that the new method of respiration lays an additional strain on the human organism and places it in the unusual conditions of existence at high altitudes. In particular, demands are made on the functional state of the nervous-psychic sphere and on the activity of the cardiovascular system and of respiration.

By analyzing all cases of abrupt deterioration of the well-being and state of the human organism, of spastic seizures and of fainting at high altitudes when breathing oxygen at high pressure on the part of our test subjects, we found that such events occurred, as a rule, during the first exercises, or during repeated exercises only when they were applied at an altitude greater than the magnitude of the excess oxygen pressure or when the partial O_2 and CO_2 pressure in the alveolar air dropped to the critical level. Sometimes a sharp deterioration in well-being at high altitudes set in because of psychogenic instability. It was obvious that familiarization climbing operations alone are not sufficient for introducing the new breathing method.

Unusual respiration with considerable resistance to expiration led to transformation of the normal breathing act and to disruption of the normal blood-circulation processes (retardation in blood flow, stagnation phenomena in the major and minor blood-circulation channels). On the other hand, the detection of pronounced degrees of anoxia and hypocapnia when breathing under high pressure, particularly at high altitudes, inevitably compelled the researchers to believe that it was necessary to carry out special preliminary training of the flying personnel to breathe oxygen at high pressure, with gradual, consistent accommodation to ever higher values of excess oxygen pressure and of climb-altitude. With repeated exercises breathing oxygen at increased pressure the test subjects, as a result of functional restructuring, were observed to adapt, to accustom the organism not only to excess pressure, but also to hypoxia and hypocapnia, if their intensity does not surpass the critical level. /245

According to our data, in order to evolve a new stereotype of respiration and adaptation by the organism to hypoxia and hypocapnia, five to seven high-altitude training exercises are necessary, with gradual accommodation to progressively higher altitudes and increase in magnitude of the excess pressure. The time of exposition at each altitude must be no less than 10-15 min, with the condition, of course, that the test subjects exhibit satisfactory endurance and comfort. It is possible, in principle, to reduce the number of sessions, but to do so it is necessary to increase the time of exposure of the test subject at any given altitude.

Psychological adaptation also sets in during the process of preliminary training, accompanied by successive and constant accommodation to increasing values of excess oxygen pressure and climb altitude.

Training for respiration of oxygen under increased pressure must be carried out taking the individual characteristics of the test subject's organism into account. In some cases it is possible to reduce the number of training sessions, and in other cases a larger number may be required to reach the desired effect. Deliberate, unreasoned reduction of the number of training sessions may lead to serious functional disorders, even to collapse or fainting.

At the present time special training of flying personnel in a pressure chamber with successive accommodation to high altitudes and increasingly high values of excess oxygen pressure is acknowledged to be the necessary condition for achieving high efficiency in the use of high-pressure oxygen respiration in flight at high altitudes.

On the basis of all that has been said above, as well as on the basis of experience gained in training flying personnel to breathe oxygen at extremely high pressure, it has become obvious that further development of a rational training schedule must be based on the physiological characteristics of high-pressure oxygen respiration, taking into account all the factors that might have a negative effect on the human organism under such conditions (oxygen deficiency, excess pressure, hypocapnia, decompression phenomena, negative psychogenic moments, etc.).

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Suggestions that successive high-altitude training of flying personnel to high-pressure oxygen respiration be replaced by two - three familiarization climbing operations in a pressure chamber or that such training be limited in general only to ground exercises must be rejected as scientifically unfounded.

Consecutive preliminary training of flying personnel and astronauts for high-pressure oxygen respiration, for gradually increasing values of excess oxygen pressure in the inspired air and of climb altitude, has, as its primary aim, the development of the human organism to adapt to all the active factors in such a situation. Such adaptation is achieved with a specific number of training sessions and sufficient exposition time.

Familiarization climbs or ground exercises alone have a different purpose and cannot bring about adaptation of the organism to the extent necessary for successful mastery of the new breathing method.

During the process of training in the new respiration method familiarization climbing operations and ground exercises as well as the showing of special training films demonstrating the new oxygen equipment and the rules for using it are necessary stages in the accommodation process. Moreover, ground exercises and familiarization climbs may be the initial link in the process of training flight personnel and astronauts in high-pressure oxygen respiration.

In real flight conditions, however, the simultaneous complex effect of all the active factors on the human organism is characteristic. Consequently, a rationally designed training schedule must, or completely as possible, take in this complex of stimuli in order to approximate the real conditions of high-altitudes and space flight.

In our opinion, the training schedule should expediently provide for a final exercise at maximum altitude at maximum values of excess oxygen pressure and, in contrast with all the other preceding exercises, should be carried out with an abrupt drop of barometric pressure within the chamber. This exercise would imitate the conditions of sudden depressurization of the cabin in high altitude and space flight and might make it possible to objectively evaluate the effectiveness of the entire preliminary training of pilots and astronauts in high-pressure oxygen breathing.

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According to our data, high-pressure oxygen respiration, complicated by a rapid, abrupt drop in atmospheric pressure, is a serious ordeal for an untrained organism. In such cases circulatory collapse and fainting have sometimes been observed.

As technical progress is made in developing the new type oxygen-respiration equipment and compensating suits it is not impossible that a certain improvement will be achieved in supplying oxygen to the organism and in damping the deleterious effect of the other factors. But we will not succeed in eliminating such deleterious effects to the same extent as achieved using a high-altitude emergency suit.

Even with the most perfect model of a high-altitude suit we will not be able to achieve uniform distribution of pressure over any part of the human body. But the nonuniform pressure distribution exerted on the human body by a high-altitude-compensation suit is the source of uncompensated excess pressure which, in turn, is accompanied by a certain degree of hypoxia and hypocapnia. And therefore even in this case it is necessary to conduct preliminary persistent training of flight personnel and astronauts in breathing oxygen under high pressure so as to adapt the organism to the unfavorable factors.

In conclusion we would emphasize once again that the development of a rational training schedule for flight personnel and astronauts in breathing oxygen at increased pressure, taking the physiological role of all the active factors into account, will help the flying personnel to accommodate faster to the new breathing method and to the new oxygen equipment sets in aircraft and will permit such personnel to make life-saving descents in an emergency situation at high altitudes during aviation and space flights.

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THE EFFECT OF PHYSICAL TRAINING UNDER NORMAL AND INCREASED
PARTIAL OXYGEN PRESSURE ON THE STABILITY OF WHITE MICE
TO TRANSVERSE GRAVITATIONAL ACCELERATION AND HYPOXIA

P. V. Vasil'yev and N. N. Uglova

In experiments on white rats it was shown that with optimal physical training programs a distinct increase was observed on the stability of the animals to overheating, cooling, irradiation with X-rays, and to certain infections and poisons [6, 7, 9, 16-19].

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Muscular training of white mice by swimming over a period of 25-60 days increased their resistance to alcohol, oxygen deficiency, high and low temperature, and also to positive acceleration [16-18]. Of course, the evaluation criterion in the latter case was the time for recovery by the mice of the capability to move in a straight line, and it is only natural that such a test does not reflect the overall resistance of the organism to gravitational acceleration. It does make it possible, however, to obtain interesting data on the characteristics of the functional state of the vestibular apparatus.

Combined application of physical training and of dibazole has proved to be more effective than separate application of each.

Analysis of the physiological dislocations that set in when a muscular load is applied [3, 5, 13, 15, 21, 22] and comparison of them with the pathogenesis of disorders occurring during gravitational acceleration have made it feasible to undertake this investigation.

The task of the present paper was the study of the effect of physical training and its combination with hypoxia on the overall stability of animals to the action of transverse gravitational acceleration and gradually developing oxygen starvation (deficiency).

Procedure

The experiments were carried out on 380 semi-mature male white mice weighing 18-25 g. Each test (trained) group had an equivalent control (untrained) group of mice exposed to the same conditions.

The muscular training was accomplished by presenting two types of physical load: primarily static and dynamic. The static load was applied by means of vertical perches, aluminum tubes of 10-mm diameter, the entire length of which was wound with vinyl chloride tape. All the tubes were mounted on a single frame. To reduce sliding by the mice, rubber rings were placed around the tubes at intervals of 3-5 cm. For the purpose of restricting the mobility of the animals and

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by preventing them from jumping off the perches, the latter were partially submerged in low-temperature water. In different experiments the degree of muscular loading was not the same, which was achieved by varying the time spent on the perches and by varying the weight suspended from the base of the tail by means of leucoplaster.

The dynamic load was achieved by having the mice swim in a bath-tub with a water temperature of about 28°.

Under high-mountain conditions (altitude 2100 m) the training was carried out only on the perches; at the same time a group of mice left in Moscow as the control group was trained by the same procedure.

After completing the training period, the animals were subjected to the effect of gravitational acceleration (45 g's, twice for ten minutes at 10-min intervals) on a centrifuge; the arm radius of the machine was 4.7 m. The rate of g-loading was 1 g/sec.

At the same time as the basic investigations to determine the stability of mice to the effect of gravitational acceleration were being conducted, small groups of animals were also being experimented with to study the effect of muscular training on stability to gradually increasing hypoxia. This was done by placing 3-5 experimental mice and the same number of control mice into hermetically sealed desiccators having a volume of 7595 ml. The moisture and CO₂ were absorbed by silica gel and soda lime. The lifetime in the closed space was recorded.

Results and Discussion

As is well known, training effectiveness is achieved by finding optimal training schedules for the problem. At the same time a very essential factor is the form of muscular loading, its magnitude and frequency of application.

N. V. Zimkin [6] indicates that only physiologically justified optical muscular stresses favor the development of progressive changes which facilitate an increase in the stability of the organism to the unfavorable effects of the environment.

On the basis of this fact we tried first of all to determine the optimal training conditions.

The first series of tests was applied to 85 mice. The training lasted 30 days. All the mice were separated into 3 equal-weight groups.

The first group was trained on perches with a 10-g weight attached to the tail. / 250 Training was carried out every other day. The duration of the first session was 3 minutes; each succeeding session was increased by 1 min. The maximum time of physical training at the end of the experiment was 15 min.

The second group was trained daily with the same load. Each day the length of the session was increased by 1 min. Thus, toward the end of the experiment it equaled 30 min.

And finally the third group served as control.

Before and after training the mice were weighed. The results of these observations are presented in Table 1.

TABLE 1. Variation in Weight (in g) of the Trained and Control Mice Over 30 Days

No. of Group	Before Training		After Training		Weight gain in % over the original weight
	No. of animals	Weight	No. of animals	Weight	
1	29	24.6	29	26.9	9.4
2	29	24.7	26	26.7	8.0
3	27	24.1	27	26.7	10.8

From the table it is evident that all the groups had approximately the same gain in weight. The observed differences in weight gain were statistically insignificant. This permits us to assume that the training was not excessive.

On the second day after completion of training the mice were rotated on the centrifuge to determine stability to gravitational acceleration. The experimental results are presented in Table 2.

TABLE 2. Endurance of the Test and Control Mice to the Effect of 45-g Loads

No. of the group	No. of animals	Outcome		Level of survival (%)	Degree of reliability with respect to the control list
		Perished	Survived		
1	29	17	12	24.8	25
2	26	12	14	24.4	22
3	27	20	7	26.9	38

By analyzing the data it can be seen that daily training was more effective. In fact, the survival rate of the second group was 53%, which is 27% greater than that of the control group. The differences in survival rates are considerable.

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Less significant results insofar as survivability is concerned was obtained with the first group, which was trained one day. The difference between this rate and that of the control group totaled 15%.

Thus, even the first series of tests demonstrated that the stability of the organism to g-loading can be appreciably increased by physical training.

The second test series was carried out with 75 mice. In this series, both static and dynamic loads were applied. The mice were divided into three groups.

The first group of animals was subjected to daily training in the form of swimming. Swimming began with 10-minute exposure, and was then increased in each session by 1 min. Swimming lasted 30 minutes in the last seven days.

The second group was trained daily on perches with a 10-g weight.

The third group served as control.

Variation in the weight of the animals during the training period is shown in Table 3.

TABLE 3. Variation in Weight (in g) of Mice During the Experiment With Physical Training

No. of group	Before adaptation		After adaptation		Gain in weight (in %) over the original
	No. of animals	Average weight	No. of animals	Average weight	
1	25	19.9	25	24.8	25
2	25	20	24	24.4	22
3	25	19.5	24	26.9	38

By comparing the data given in Table 3 it can be seen that the mice of the test groups gained less weight than the control mice. The level of physical loading of these animals was approximately the same.

After completing the training period, the mice was subjected to the effect of 45-g's. The results of centrifuging are given in Table 4.

TABLE 4. Survival Rate of Test and Control Mice Subjected to a Load of 45-g's.

No. of group	No. of mice	Outcome		Survival rate (%)	Degree of reliability
		Perished	Survived		
1	20	8	12	60	1.8
2	22	6	16	72	2.8
3	21	14	7	33	-

Analysis of the data confirmed the results of the preceding series. As a matter of fact, the most clearly positive effect on the resistance of the animals showed up after moderate uniform static loading: the survival rate in the second group was 39% higher than in the control group. The differences are statistically reliable. A somewhat lesser, but completely satisfactory effect was also obtained

in experiments with training by daily swimming. The stability to gravitational acceleration in this group was 27% higher than in the control group. /252

Thus, the overall resistance of the white mice to high gravitational acceleration can be substantially enhanced by rational static as well as dynamic training.

It was of great interest to find possibilities for increasing the stability of animals to gravitational acceleration by combined application of physical training and acclimatization to conditions of moderate hypoxia.

For this purpose, we laid on a third series of experiments with 150 mice under high-mountain conditions.

The male mice were divided into 5 equal-weight groups:

- 1) control groups (in Moscow);
- 2) physical training (in Moscow);
- 3) acclimatized group at an altitude of 2100 m (Terskol);
- 4) acclimatized for 2 weeks at an altitude of 2100 m and 2 weeks at an altitude of 3800 m (Ledovaya base);
- 5) physically trained group at an altitude of 2100 m (Terskol).

The original weight of the mice before beginning the experiment fluctuated between 15 and 18 g.

The mice were acclimatized to high-mountain conditions in the area of Mt. Elbrus.

The training of the animals took place every other day. In the first two weeks the weight of the load was 20 g, which corresponded to approximately 100% of the body weight. The training period of 10 min in the first session was increased by 1 min in each succeeding session.

In view of the fact that the mice located at Terskol did not succeed in holding up the load after the 10th day, the weight was decreased to 10 g. This change in procedure was done simultaneously in Terskol and Moscow. Training and acclimatization to high-altitude factors was completed four days before the first rotation on the centrifuge.

Deserving of primary attention is the fact that the weight of the animals did not change equally. The control mice also exhibited the greatest gain in weight; the greatest lag in weight was found in the animals of the fifth group, which were subjected to loading under high-altitude conditions. /253

The test of stability to gravitational acceleration was conducted on the fourth day after returning to Moscow. The results of these experiments are presented in Table 5.

From the given data it is evident that in all the test groups, without exception, the survival rate was higher than in the control group; in the third group, which was located at an altitude of 2100 m above sea level, it was 5.2% higher

TABLE 5. Survival Rate of White Mice Subjected to 45-g Loading Four Days After Acclimatization

No. of group	Experimental conditions	No. of mice	Survival	Survival rate	t
1	Control	28	11	39.2 ± 9.2	
2	Physical training in Moscow	25	14	56.0 ± 9.6	1.3
3	2100 m	27	12	44.4 ± 9.6	0.37
4	2100 + 3800 m	30	19	63.4 ± 9.1	1.9
5	2100 + physical training	29	20	69.0 ± 8.6	2.4

than in the control group, whereas in the fourth group it was 24.4 and in the fifth group 29.8% higher.

Although in statistical processing the difference is significant only in the fifth group, the overall regularity of the increase in survival rate permits us to consider the results as evidence of the positive effect of acclimatization and physical training.

At the same time, active acclimatization, which consisted of a combination of the effects of physical stress and hypoxia, proved to be more effective than passive acclimatization (exposure to high altitude).

The mechanism of the favorable effect of physical training under normal as well as increased partial oxygen pressure is complex; as a matter of fact, in the case of overall physical strain, the reaction takes in almost all the systems of the body, directing efforts to satisfy the increased demand of the body with respect to bioenergy. This is accompanied by an increase in pulmonary ventilation, cardiac activity, erythrocytosis, increased myoglobin, increased glutathione content, higher activity of carbonic anhydrase of the blood, and by other changes [2, 10, 12]. Physical training also promotes the development of the anaerobic component of energy processes in the muscles [4].

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All of this activity is oriented toward overcoming by the organism of the deeper and more prolonged hypoxia that arises in the case of specific levels of physical strain as well as acceleration.

In our experiments on 70 white mice to determine stability to gradually increasing oxygen deficiency it was clearly established that the lifetime of the experimental animals was substantially greater than that of the control animals.

The results of these experiments are given in Table 6.

These data agree with the observations of A.F. Aleksandrov, P.I. Yegorov, A.N. Krestovnikov, et al. [1, 10].

TABLE 6. Lifetime of Trained and Untrained Mice in the Case of Gradually Increasing Hypoxia

Test Series	Experimental conditions	M $\pm$ m (min)	t
I.	Control group	99 $\pm$ 14.0	-
	Trained in swimming for 30 days	162 $\pm$ 10.4	3.15
	Trained on perches with a 10-g weight	140 $\pm$ 17.4	1.69
II.	Control group	107 $\pm$ 0.65	-
	Trained on perches in Moscow	144 $\pm$ 8.2	4.5
	Acclimatization at 2100 m	114 $\pm$ 3.5	1.96
	Acclimatization and training on perches at 2100 m	151 $\pm$ 7.5	5.84

Thus, our investigations have demonstrated that under optimal programs of static as well as dynamic physical training the stability of test mice to the effect of g-loading increases appreciably. Particularly favorable is the combined application of physical loading and moderate levels of hypoxia.

The results of these experiments and comparison of them with clinical physiological reactions to the effect of hypoxia and weightlessness (decrease in mass of circulating blood, plasma loss, reduction of the number of erythrocytes, deterioration in the blood supply of a number of organs and tissues, reduction of muscular tonus and of the overall resistance of the organism to gravitational loads, disruption of metabolism, etc.) permit us to suggest that the method of physical training under periodically created moderate hypoxia may be an effective means for maintaining high stability in the organism of astronauts in the case of prolonged flights.

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EFFECT OF A DIFFERENT RATE OF GROWTH OF ANOXIA ON THE VEGETATIVE FUNCTIONS AND BIOELECTRIC ACTIVITY OF THE BRAIN OF A DEVELOPING ORGANISM

I. G. Dallakyan and G. M. Nikitina

As yet but little study has been devoted to the significance of the rate of increase of oxygen deficiency in the development of compensatory reactions and to survival of the organism in the case of anoxia. There are indications in the literature that at a slower rate of environmental atmospheric rarefaction the stability of the organism is higher than at a rapid rate of development of anoxia [1]. An opposite relationship has been discovered, however, in a number of cases [13].

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Investigations with human beings have revealed that at extraordinarily low rates of increase of decompression (tens of hours), the "altitude ceiling" turns out to be lower than at high rates.

Within the framework of clarifying the compensatory mechanisms of the central nervous system in the case of anoxia it is of interest to study the features of bioelectric response of the brain. The fundamental electrophysiological investigations are concerned with the effect of acute oxygen starvation in the case of anoxic anoxia on the EEG of a mature organism [9, 11, 15].

Some data on the character of the change in electrical activity of the brain during various degrees of anoxia in animals and man at various age levels have been given in [3, 4].

Ye. L. Golubeva [3, 4] describes the genesis, in the reticular formation of the midbrain and of the optic thalamus of rabbits, of synchronized rhythm (4 - 7 oscillations/sec) when the CO₂ content in the inspired air is from 1-10%. This synchronized rhythm was more pronounced after the fifth or sixth day of life. In the cortical regions of the brain the synchronized activity observed in rabbits in the first few days after birth changes to unsynchronized activity after the sixth to tenth days. The author arrives at the conclusion that this represents early maturing of the mechanisms which maintain the internal medium of the organism constant.

In all the cited papers dealing with the electrical activity of the brain in the case of oxygen deficiency of the mature and developing organism the method of rapidly increasing anoxia was used.

At the same time, a study of the characteristics of variation in the bioelectric activity of various brain structures during slowly increasing anoxia may be of considerable importance in solving the problem of the compensatory capabilities of the organism during prolonged space flights.

In solving this problem the ontogenetic aspect of the investigation should provide good assistance, since it is easier to clarify the fundamental mechanisms of compensatory reactions of the integral organism to anoxia during the formation of gradually more complex forms of reactions and of relations within the central nervous system.

The aim of the present investigation is to study the dynamics of changes in the bioelectric activity of a number of regions of the brain and of the vegetative functions of a developing organism at a varying rate of increase of anoxic anoxia.

Investigational Procedure

The investigation was carried out in chronic experiments on 30 rabbits varying in age (from 4 to 90 days). The anoxia was produced in a pressure chamber at two rates of "climb"—2 and 15 m/sec. During the experiments we measured:

a) the character, sequence and depth of changes in the bioelectric activity of regions of the neo- and archi-pallium (the motor, optic, the anterior and posterior limbic regions, of the neopallium, and the hippocampus) and of a number of subcortical nonspecific formations of the thalamus, of the posterior hypothalamus, the reticular formation of the midbrain, all of which form part of the limbic system of the brain;

b) the relationship between changes in EEG and vegetative functions and respiration and cardiac activity.

Biopotentials were elicited by electrodes incorporated bipolarly at symmetrical points of the hemispheres.

The subcortical Ni-Cr electrodes were machined electrolytically [5] to a point diameter of 100–150 microns and were inserted by means of a stereotaxic Horsley-Clark instrument. The diameter of the cortical electrodes (extradural) was 300 microns. The coordinates of the selected points were determined by the stereotaxic charts of Sawyer, Everett and Green with appropriate recalculations for the species and age of the test animals [10].

In order to make a control test, the brains of the animals coming from the experiment were fixed in a 10% solution of formaline, and then sections 120–150 microns thick were cut on a freezing microtome (Figure 1). The respiration was recorded by means of a thermistor [2], and the EKG by means of silver-foil electrodes.

After the period of adaptation of the animal to the environmental situation has expired (15–20 min) the initial background of respiration, EKG and EEG is recorded, and then "altitude" is reached at the given rate. The functions being studied are recorded at each 1000 m of "climb" until respiration ceased or until there is an abrupt interruption of cardiac activity. "Descent" from the final altitude was at a rate of 100–150 m/sec. In part of the experiments records

were made continuously during the entire descent period until the indices being studied were recovered.

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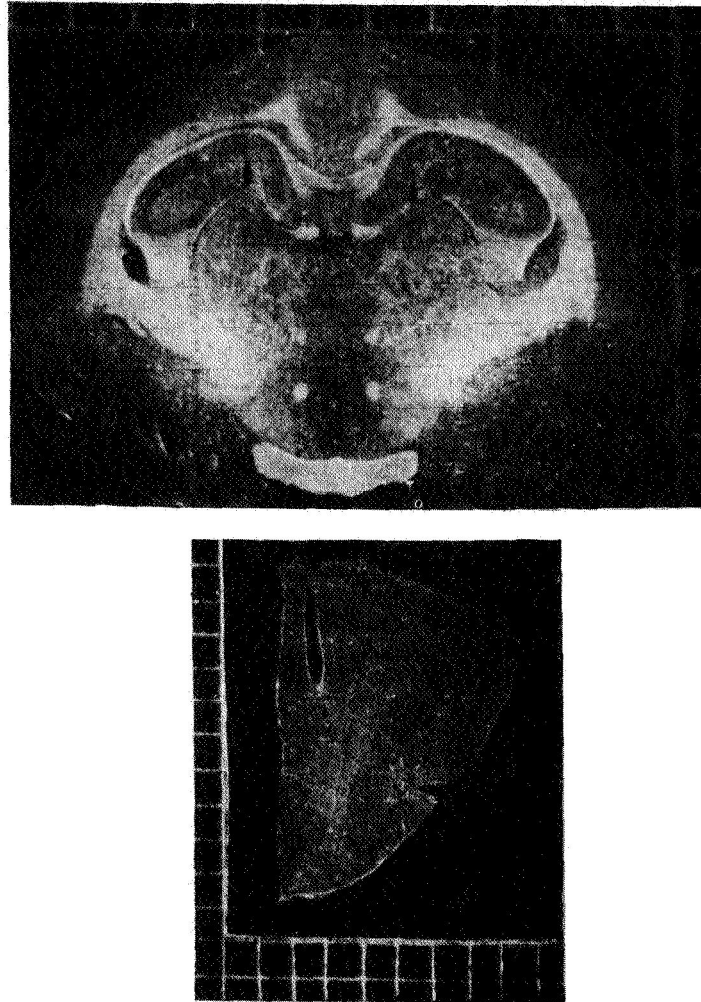


Figure 1. Morphological Control of the Correctness of Arrangement of the Electrodes. Traces of the Tips of the Electrodes in the Hippocampus and Anterior Limbic Cortex are Visible in the Frontal Section of the Brain of a 37-Day-Old Rabbit.

In control experiments on 17 rabbits of different age the pattern of bioelectric reaction of the brain and the vegetative components were monitored for 2-5 hours without the effects of anoxia.

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Results of the Investigations

In rabbits up to 20 days old the difference in magnitude of the "altitude ceiling" at the two "climb" rates used is statistically reliable: the rarefaction rates were 2 m/sec for 13,000 m and 15 m/sec at 11,000 m. In rabbits 35-90 days old the altitude ceiling is not reliably ($P = 0.05$) different in magnitude at "climb" rates of 2 and 15 m/sec (10,610 and 10,900 m), respectively (Table 1).

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TABLE 1. Comparative Data of the Variation in Altitude Stability of Young and Old Animals at Various Climb Rates

Climb at a rate of 2 m/sec				Climb at a rate of 15 m/sec			
No. of animals	Age (days)	Altitude stability		No. of animals	Age (days)	Altitude stability	
		Time (min)	Ceiling (m)			Time (min)	Ceiling (m)
			Age group (young)				
6	4	98	11,800	6	7	13	11,000
12	6	108	13,000	13	10	10	9500
13	9	97	11,500	29	13	14	11,700
14	12	127	15,250	30	19	14	12,000
14	15	108	13,000				
15	17	116	13,900				
Average		109	13,000	Average		12	11,000
Age group (old)							
7	30	78	10,000	23	27	13	11,500
9	32	89	10,500	29	31	15	13,000
3	35	76	9500	27	48	11	10,000
4	37	83	10,700	20	58	12.5	11,800
11	41	104	12,500	10	48	13	12,000
3	49	100	12,000	21	60	12	11,000
10	50	94	11,300	27	45	11.5	10,400
21	53	85	10,300	98	78	11	10,000
22	85	83	10,000	21	64	11	95,000
25	48	83	10,000				
26	45	83	10,000				
Average			10,610	Average			10,960

At rarefaction rates of 2 m/sec, the first hypoxic reaction in rabbits of all ages is exhibited by the function of respiration. A change in respiration appeared already at altitudes of 1000-3000 m (Fig. 2A); it is manifested primarily by use in frequency of respiratory motion and a decrease in amplitude of motion. In rabbits up to 20 days old the respiration frequency increases during the period on the average by 10-20%, and from 30 to 70% in the older rabbits.

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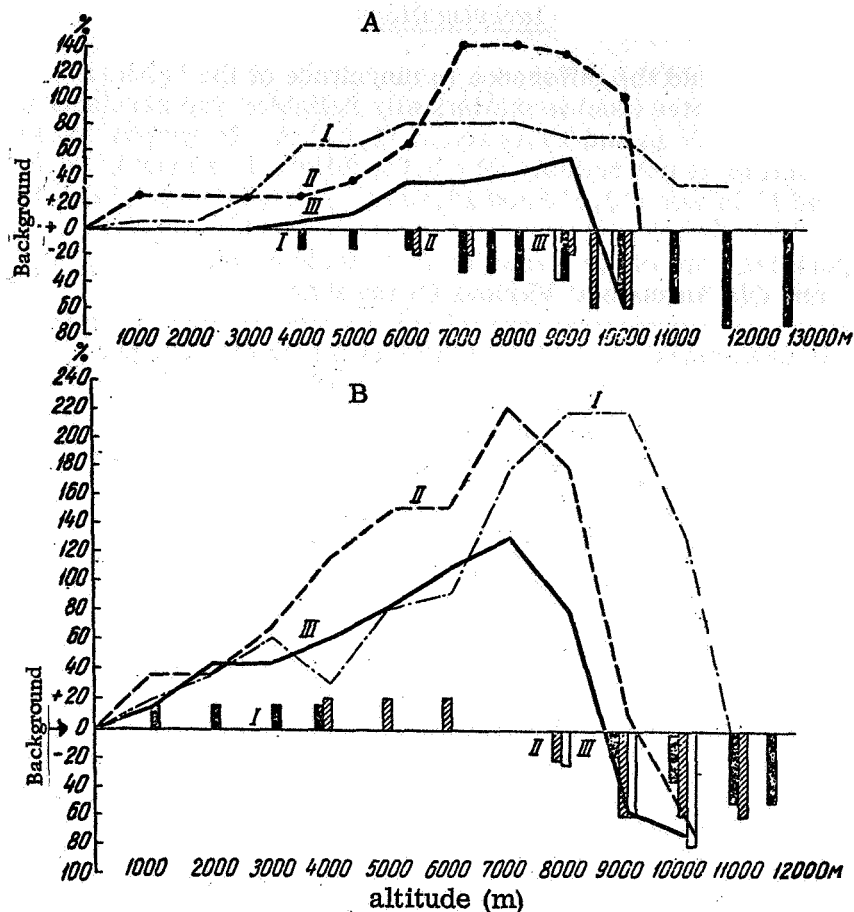


Figure 2. Dynamics of Measuring the Respiration (curves) and Cardiac Activity (columns) in Rabbits Aged (in days) 6 (I), 45 (II), and 85 (III) with Increasing Anoxia to a Rarefaction Rate of 2(A) and 15 m/sec (B).

At altitudes of 4000-9000 m changes in cardiac activity appears in the form of a gradual decrease in heartbeat frequency (Figs. 2A and 3A). In the early age period the disruptions of cardiac rhythm appear earlier (4000-6000 m), as a rule, than in later stages of development (6000-8000 m). As the degree of oxygen deficiency increases, the depth of deviations in the vegetative functions increases. Characteristics of the lower age groups is the parallel increase in the respiration rate and attenuation of the heartbeat; in the higher age groups (after 20 days), however, the heartbeat frequently slows down earlier, in the period when the reaction of the respiration rate drops (Fig. 2A).

In the case of rarefaction at a "climb" rate of 15 m/sec, a similar sequence of inclusion in the hypoxic reaction of the vegetative functions is noticed only in rabbits of the higher age groups (35-90 days) [Fig. 3B]. In the younger animals the variations in EKG and respiration appear simultaneously (from 1000-2000 m), and the intensity of the respiratory reaction is almost double that at a "climb" rate of 2 m/sec (Figs. 2A and B).

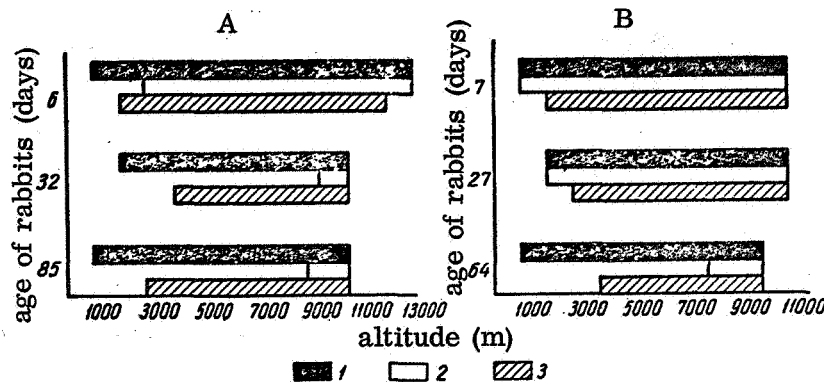


Figure 3. Sequence of inclusion in the hypoxic reaction of respiration (1), cardiac activity (2) and bioelectric cerebral activity (3) in rabbits of different ages at a "climb" rate of 2 (A) and 15 m/sec (B).

Changes in the cardiac activity at "climb" rates of 2 and 15 m/sec are different in character: in the first case the anoxic reaction shows up from the very start as damping of the heartbeat, and in the second case the original phase (up to 7000 m) is an increase in rate of heartbeat (Figs. 2A and B); in older rabbits more intense qualitative changes in EKG are observed (atrioventricular blockade, scintillating arrhythmia, palpitation of the ventricles).

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Initial variations in EEG of the cerebral regions being studied appear in rabbits up to 45 days old with a "climb" rate of 2 and 15 m/sec at exactly the same altitudes (2000-3000 m). Changes in EEG with age at a climb rate of 15 m/sec begin to appear only beginning with 4000-5000 m (Figs. 3A and B).

The dynamics of changes in EEG in young rabbits (up to 20 days) at a climb rate of 2 m/sec consist of 6 successive phases: I - decrease in amplitude and, in a number of cases, damping of the oscillation frequency; II - appearance of groups of synchronized waves of the spindle type (4-7 Hz); III - increasing reduction in amplitude and damping of rhythm; IV - predominance of slow waves (2-4 Hz) of relatively low amplitude, the appearance of spikes; V - alternation of electric activity with periods of electric silence; VI - complete electric silence (Fig. 4).

In older rabbits subjected to advancing anoxia at the given climb rate, the I stage is manifest in a rise of oscillation amplitude connected with damped rhythm (Fig. 5-1, a, b); a constant synchronized rhythm of 7-8 Hz appears in the second stage; characteristic in the IV stage in the appearance of high-amplitude (up to 300 microvolts) slow (0.2 - 1.5 Hz) waves; stages IV, V and VI are of short duration and follow each other rapidly (Fig. 5, 1 c, d, e).

In young rabbits (up to 20 days) at a "climb" rate of 15 m/sec, in contrast with the corresponding group of animals at a "climb" rate of 2 m/sec, the successive EEG phases appear at high altitudes, except for the first phase of initial changes. Thus, phase II of characteristic synchronized waves (spindle-shaped groups) in the case of rapid development of anoxia (15 m/sec) shows up

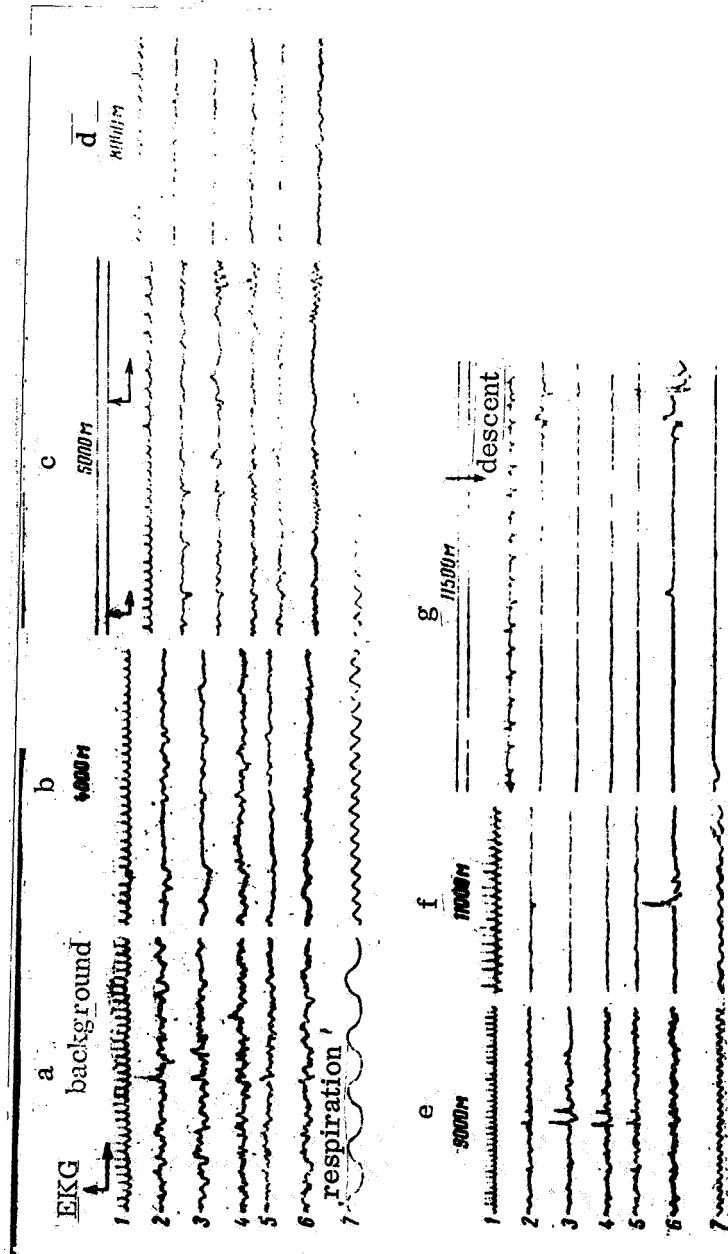


Figure 4. Dynamics of Phase Variations in Bioelectric Activity of the Cerebral Regions Being Studied for Thirteen Rabbits (the Experiments Began at the age of 4 Days) at a Climb Rate of 2 m/sec. a-Background; b-f-Phases I to VI; g-Phase II at a Rarefaction Rate of 15 m/sec (6 Rabbits, Experiments Began at the age of 7 Days); 1-EKG; 2-6-EEG, Sensorimotor, Anterior Limbic Cortex, Hippocampus, Hypothalamus and Reticular Formation of the Midbrain, Resp., 7-Pneumo-gram. Calibration is 50 Microvolts, 1' sec.

in the EEG at an altitude of 8000 m; at the slow rate of rarefaction (2 m/sec), this phase appears already at an altitude of 6000 m (Fig. 4, c, g). The stage of pronounced "spike" waves is absent in the majority of cases.

In rabbits of the older age group, phase changes in EEG characteristic of the 2 m/sec rate are reduced (at the 15 m/sec rate): the initial changes in bioelectric activity are manifested in a reduction of amplitude, increase in rhythmic frequency accompanied by the simultaneous appearance of a synchronized rhythm of 6-8 Hz (Fig. 5, II, a, b); the three subsequent phases (slow waves, alternation of and suppression of electric activity) are very fast. Absolute electric silence does not show up in some cases, even when respiration completely stops. In the last phases the qualitative changes in cardiac activity, namely, atrioventricular blockade, scintillating arrhythmia, palpitation of the ventricles, seldom occur (Fig. 5, II, c, d).

Against a background of increasing phase changes in the EEG in the case of slowly advancing anoxia (2 m/sec) there occur periods in which the electric activity returns in frequency or amplitude to the original value. Such "compensation" is unusually noted at altitudes of 4000, 7000 and 10,000 m, but more frequently at altitudes of 6000-7000 m, which corresponds to the period in which the compensating capabilities of the vegetative functions show up as being more pronounced. Periods of "compensation" of bioelectric cerebral activity also are found at the higher rate of "climb" (15 m/sec) at altitudes of 7000 and 9000 m.

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The bioelectric reaction of the brain (all the described phase changes of the EEG) at a "climb" rate of 2 m/sec frequently occurs in the cortex regions, the sensomotor region of the neocortex and the anterior limbic cortex, which is morphologically related to the former [14]. With an increase in the degree of oxygen deficiency the changes in EEG appear in the subcortical structures, the reticular formation, the posterior hypothalamus, and also in the region of the hippocampus (archipallium) and posterior limbic subregion of the neocortex. Most stable to the more intense levels of anoxia are the structures of the posterior limbic cortex and of the posterior hypothalamus, where changes evolve in parallel.

In contrast, at a "climb" rate of 15 m/sec it is not possible to find out which structures are most stable when the phases change rapidly in succession. Changes in EEG occur almost simultaneously in the cortical and subcortical structures.

Restoration of the investigated vegetative and EEG indices after the action of anoxia takes place in the following order: first the cardiac activity is restored, then the respiration, and finally the bioelectric activity of the brain.

The pattern of restoration of the bioelectric activity of the brain after the effect of anoxia at a rarefaction rate of 2 and 15 m/sec has a "specular" nature; the background EEG is restored through the slow and synchronized wave phases, which are particularly clearly pronounced in the reticular formation, the hypothalamus and the hippocampus (Figs. 6, Ib and IIa).

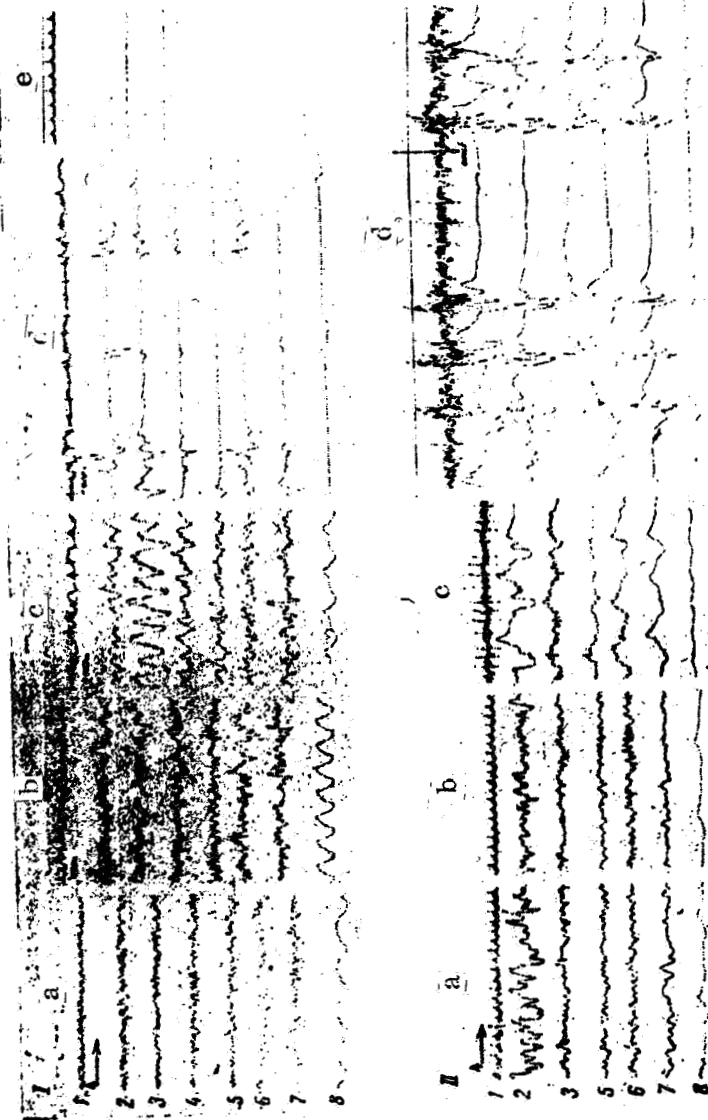


Figure 5. Comparative Characteristics of the Evolution of Phase Changes of EEG in 10 and 23 Rabbits of Higher age (30-50 Days) at a "Climb" Rate of 2(I) and 15(II) m/sec. a-Background; b-I; c-e-EKG; 2-7-EEG of the Sensomotor, Anterior Limbic, Posterior Limbic Regions of the Cortex, Hippocampus, Hypothalamus, and Reticular Formation of the Midbrain, Resp; 8-Pneumogram; Calibration—50 mV, 1 sec.

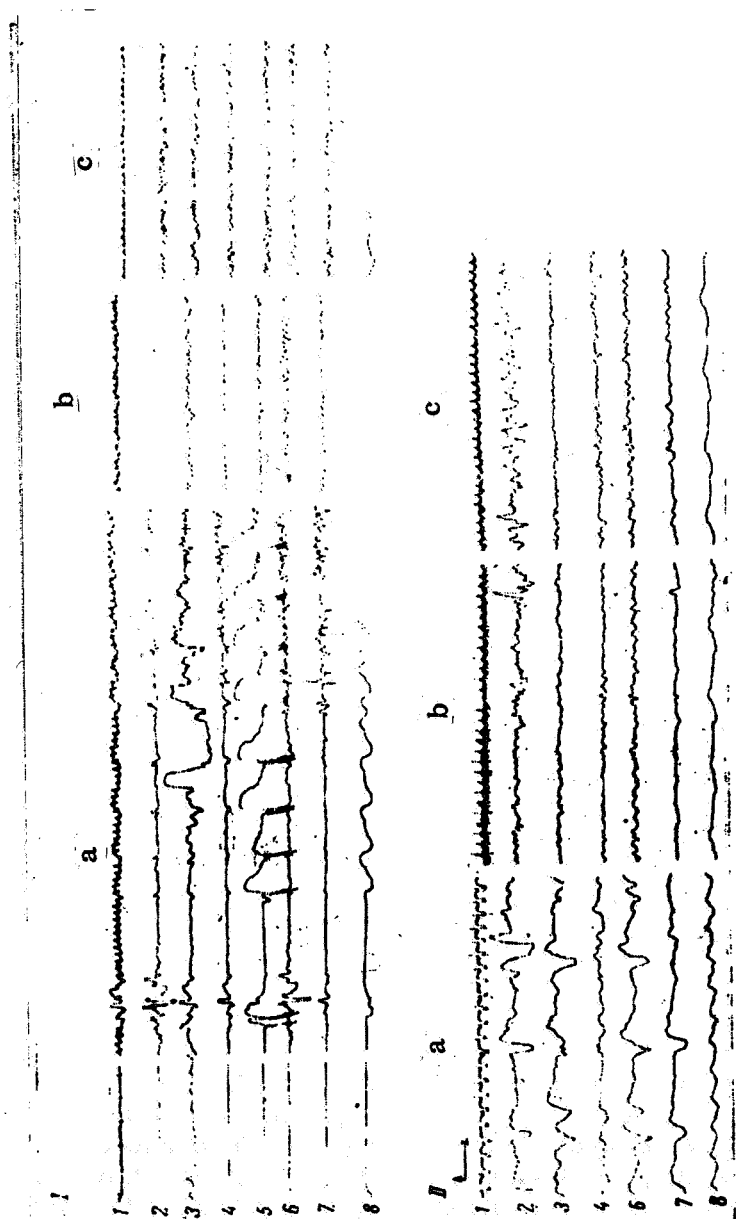


Figure 6. Dynamics of Restoration of Bioelectric Cerebral Activity in Older Rabbits After Anoxia Evolving at a "Climb" Rate of 2(I) and 15(II) m/sec. a-During Descent. The Notation for the Lines in I a-c is the Same as in Fig. 5; in II a-c: 2-Optical Cortex; 4-Thalamus.

In order to restore the background electric activity in young rabbits, as compared with old ones, more time is required both at a "climb" rate of 2 and 15 m/sec; in the latter case, however, the break in time of restoration is less significant.

In animals of the same age, restoration of the bioelectric activity when the rarefaction rate was 15 m/sec proceeded somewhat faster than when the rate of advance of anoxia was 2 m/sec.

Conclusion

These investigations show that the adaptive reaction of the organism to anoxia from the very early stages of positive evolution is complex, consisting of a number of functional components. It covers both vitally important vegetative functions, namely, respiration and cardiac activity, and bioelectric processes in the cerebral tissue. Variations of the vegetative indices and biopotentials in various cerebral structures of developing animals are characterized by phase-type evolution namely, successive transition from one phase of the anoxic reaction to the next, all the way to complete disruption of the functions being studied when the oxygen deficiency reaches low levels. The relationship between the various functional indices (vegetative changes and variations of EEG) is examined for a mature organism [9]. Insofar as the features of the indicated correlations in the light of age are concerned, papers are available from Czech authors (Ilec, Maurec, Fischer, and Krulik) in which the emphasis is on the study of the biochemical structural and functional changes.

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Both the age characteristics of evolution and the factor of rate of increase of anoxia have an effect on phase changes of the functions we studied.

The singular nature of the original phase of variations in EEG during the early days of growth is manifest not in the activation of high-frequency oscillations, as in the case of a mature organism [9], but in the attenuation of the rhythm. In older animals, as compared with younger ones, the final phases of suppression of bioelectric activity and the accompanying serious disruption of the vegetative functions are seen to be of lesser duration. Better differences in EEG, namely, reactions to anoxia in the cortical and subcortical structures, are observed with age. All this is governed by the degree of maturity of the nervous regulatory mechanisms in this or that stage of autogenesis.

The rarefaction-rate factor makes a considerable contribution to the development of compensatory reactions of the growing organism: the faster the rarefaction, the later (at higher altitudes) intense changes in the bioelectric activity of the brain and in vegetative functions appear. This is especially true of older animals, which have a sufficiently mature central nervous system and more perfect compensatory mechanisms. Therefore they have almost no difference in magnitude of the altitude ceiling at the two given rarefaction rates (2 and 15 m/sec). In contrast, young animals have a considerably lower altitude ceiling at the faster rate of increase of anoxia because their adaptive mechanisms are incomplete.

At the rarefaction rate of 15 m/sec the compensatory reaction, estimated on the basis of EEG, usually involves a large number of cerebral structures simultaneously. In contrast, at the slower rate of increase in anoxia (2 m/sec) the time sequence of onset of changes in the cortical and subcortical structures is more clearly pronounced. The above-mentioned fact of synchronization of changes in the bioelectric activity of the hypothalamus, hippocampus, and posterior region of the limbic cortex indicate that structures of the limbic system of the brain participate in the defense reaction of the organism as a unified functional system. The unified participation of the nervous mechanisms of this system in maintaining functions important for the vital activity of the organism at a specific level in the case of oxygen deficiency is ensured by the existence of morphological and functional links between the indicated cerebral structures [6-8, 11].

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THE INFLUENCE ON MAN OF A LONG STAY UNDER CONDITIONS OF REDUCED BAROMETRIC PRESSURE AND RELATIVE ISOLATION

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Assuring the vital activity and capacity for work of man on long flights in present and future flight apparatus is one of the central problems of aviation and space flight. This problem involves a complex set of questions, among which the following are important: selection of the best pressure regime within the space ship, establishment of the proper daily rhythm of work and rest for the astronaut, prolonged isolation, etc.

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At the time the present study was undertaken (1958) there were only scattered references in the literature to certain works which discuss the possibility of man remaining for a long time (up to four days) in an environment with a modified gas composition and reduced barometric pressure (A.P. Apollonov, D.I. Ivanov, M. Ye. Marshak, and V.A. Spasskiy,).

In addition to this we were also acquainted with the work of A.M. Genin, O.G. Gzenko, A.D. Seryapin, N.N. Gurovskiy, and others, which showed that man could remain for 10-15 days in relatively small chambers at reduced barometric pressure (elevation 5000 m). There was also information concerning an experiment carried out by the American flyer Farel, who remained for 7 days in a barochamber of small size (2.5 m^3) at a height of 5500 mm. This experiment studied, in addition to the effects of rarefaction, the influence of specially developed "daily" cycle (14.5 hr).

The work described above should be considered as a first attempt to solve experimentally the question of choosing proper pressure conditions within the cabin of a space ship and the scientific establishment of a regime of sleep and wakefulness for the astronaut.

Selection of the proper pressure conditions in the cabin of a spaceship requires that one take into account both the engineering and the medical aspects. The first aspect involves the weight and strength of the cabin. The second concerns the conditions of human life. Available data in the field of aviation physiology have provided a basis for assuming that one of the appropriate pressure regimes in the cabin may be a pressure of 380 mm Hg (a height of 7000 m). But the question of a prolonged stay under these conditions has remained open and has been in need of experimental solution. The permissibility of a very thin atmosphere for these purposes is related to the hazard of the development of decompression disturbances.

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The studies undertaken by us had two goals:

— to study the possibility for man to remain for a long time (up to 30 days) in small chambers with reduced atmospheric pressures corresponding to heights of 3000, 5000 and 7000 m, with the pO_2 in the air ranging between 150 and 200 mm Hg; and

— to determine the nature and direction of functional changes in relation to disturbances of the normal daily regime.

Method of Investigation

The studies were carried out in a specially outfitted pressure chamber with a net volume of 5 m³. The gas composition of the atmosphere, the temperature regime, and the humidity were maintained within given limits with the use of re-generation apparatus. Two persons participated in the experiment simultaneously. An individual daily regime was worked out for each of them, and each alternated in repeated experiments. The duration of the experiment ranged from 10 to 30 days. The general pattern of the experiment and the daily regime are shown in the following schedule.

Time of day	Regime No. 1	Regime No. 2
9.00	Enters on duty	Goes of duty
9.10—9.50	Physiological and hygiene studies	
9.50—10.30	Breakfast	
10.30—11.50	Clinical studies	
12.00—14.00	Duty	Daytime sleep
13.30—14.00	Physiological and hygiene studies	
14.30	Dinner	
15.00—17.00	Daytime sleep	Duty
17.00—19.00	Clinical and hygiene studies	
19.30	Supper	
20.00—20.30	Physiological and hygiene studies	
20.30	Duty	Night time sleep until 2:30 AM
1.00—2.50	Clinical and hygiene studies	
3.00	Night sleep until 9 o'clock	On duty until 9 o'clock
5.00—7.00	Physiological and hygiene studies	

The subjects being studies were fed with preserved and concentrated food products with a vitamin complex added.

Observations were made during the experiment on certain aspects of higher nervous activity (behavior, residual time reflex, critical frequency of flicker

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fusion, visual perception time, color perception, and differential time thresholds), electroencephalograms, electrocardiograms, breathing, arterial pressure, body temperature, reaction of the cardiovascular and respiratory systems to measured physical stress also with restrained breathing, energy consumption of the organism (after Holden), protein fractions in the blood plasma (by the electrophoresis method), and the content of 17-oxycorticosteroids in the urine. The electroencephalograms were recorded with mono- and bipolar leads from the occipital and frontal regions and were subjected to frequency analysis. We also determined the total EMF, the EEG, and the EMF of individual components of the EEG rhythms.

The program also provided for detailed clinical and physiological examination of the persons taking part in the experiment. The hygienic studies (barometric pressure, content of O_2 and CO_2 , temperature, and humidity) were done 6 times per day.

Results of the Investigation

Seven persons took part in the study. Table 2 and Figs. 1 and 2 give a general description of the experimental conditions, the length of the experiment, and the results.

It is apparent from the data given that pO_2 in the expired air ranged from 150 to 200 mm Hg; the pCO_2 , from 2 to 14 mm Hg; the air temperature in the pressure chamber, from 18 to 27 C; and the relative humidity, from 30 to 75%. In particular cases the relative humidity dropped to 10-30%.

Figure 3 gives comparative data on changes in pulse frequency, breathing, and the arterial pressure in experiments at heights of 3000, 5000, and 7000 m, lasting 10 days.

The changes observed under these conditions did not exceed physiologically permissible limits. Analysis of the EKG's showed that under the conditions of the experiment changes were observed in the position of the electrical axis of the heart.

Maximum deviation of the cardiac axis to the left (from 13 to 30°) was observed at a height of 7000 m, a phenomenon associated with the higher position of the diaphragm (height meteorism). Sometimes the position changes of the cardiac axis were more complex in nature, as indicated by the simultaneous increase of the R peak at all three leads.

The electroencephalograms showed no changes indicating an effect from atmospheric rarefaction within the limits of the studies. Periodic variations in the α and β rhythms (14-20 Hg) are of interest, as well as the total EMF of the EEG as a function of the time of day at which the record was made.

From a frequency analysis of the EEG it was found that slow waves of the delta type are a constant component of the electroencephalogram during the period of wakefulness both during the day and at night. As for the number of these

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Certain Parameters in the Pressure Chamber

Dates of the experiment	Last name of subjects	"Height," m	pO ₂ , mm Hg	pCO ₂ , mm Hg	Relative humidity of the air, %	Air, C°	Length of stay, days	Daily regime of subject	Remarks
March 15-28	P-n	3000	150-180	2-13	40-70	20-24	13	No. 1	Experiment concluded upon completion of program
The same	P-v	3000	150-180	2-13	40-70	20-24	13	No. 2	The same
April 18-28	Pod-v	5000	150-190	2-8	45-68	18-24	10	No. 2	The same
The same	F-k	5000	150-190	2-8	45-68	18-24	10	No. 1	The same
July 22-August 1	Pod-v	7000	156-175	3-14	50-60	25-26	10	No. 1	The same
The same	F-k	7000	156-175	3-14	50-60	25-26	10	No. 2	The same
May 24-June 23	P-n	3000	160-200	2-12	50-75	20-27	30	No. 1	The same
May 24-May 29	P-v	3000	160-200	2-12	50-75	20-27	4	No. 2	Removed from pressure chamber with elevated body temperature
May 30-June 9	D-v	3000	160-200	2-12	50-75	20-27	10	No. 2	Upon conclusion of experiment
June 13-23	K-n	3000	160-200	2-12	50-75	20-27	9	No. 2	
November 15-December 16	F-k	7000	150-200	2-12	30-45	20-23	30	No. 2	Experiment concluded upon completion of program
The same	K-n	7000	150-200	2-12	30-45	20-23	30	No. 1	

Dereriation in the condition of subjects P-v and D-v was the result of factors not directly related to the condition of the experiment.

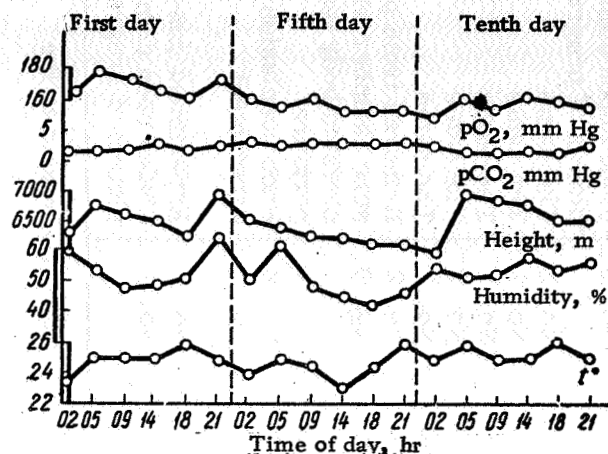


Figure 1. Changes in the Microclimatic Indexes in the Pressure Chamber on the First, Fifth, and Tenth Days of the Experiment

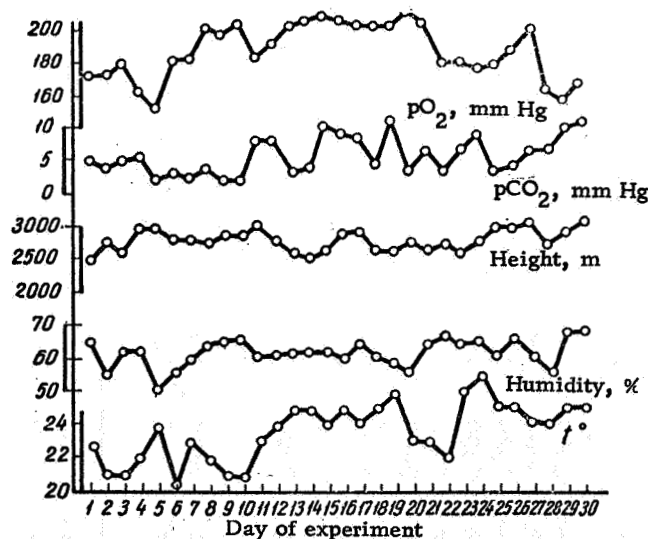
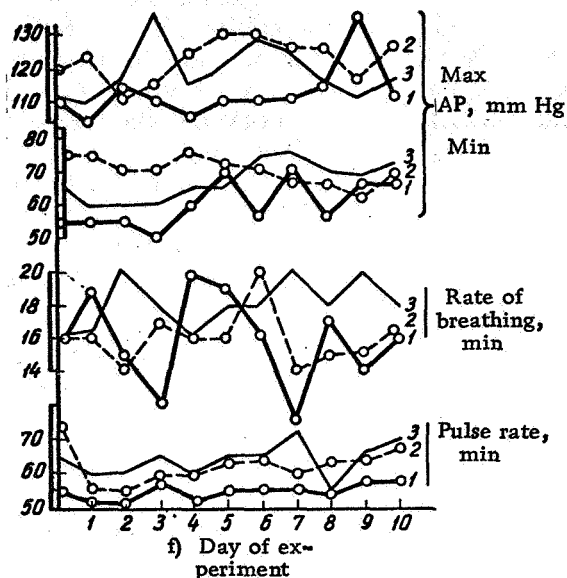


Figure 2. Changes in the Microclimatic Indexes in the Pressure Chamber During a 30-Day Experiment (Measurements at 9 AM).

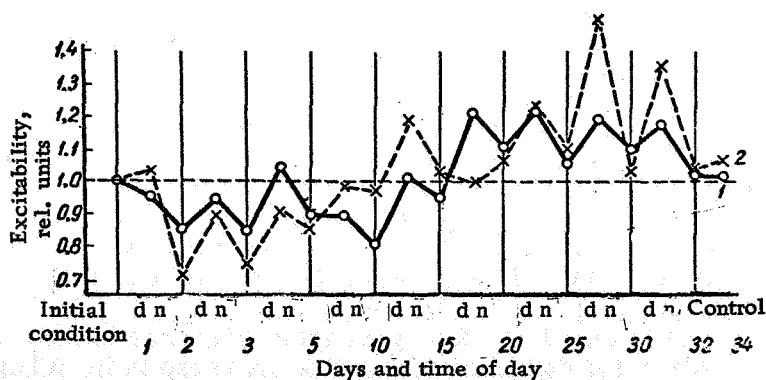
waves, this was very variable. In evaluation of the nature of the EEG it is apparent that the deviations observed at all heights were for practical purposes within normal limits. Nor were any appreciable deviations observed in a study of the delayed (20 sec) motor time reflex. The changes observed were individual in nature and did not exceed the magnitudes observed under conditions of ordinary activity of the subjects. A greater variability of the time curve of the reflex could only be observed toward the end of the experiment (according to the data of V.T. Lebedeva).

Figures 4 and 5 show the changes in the critical frequency of flicker fusion and differential time thresholds in subjects P-n and P-v in a 30-day experiment at a height of 3000 m. It is apparent that in the case of subject of P-n there is reduced function during the first 10 days and, in the succeeding period beginning with the 15th day, there was a contrasting increase. This variation in function evidently reflects a reconstruction process of the organism.



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Figure 3. Change in Arterial Pressure (AP), Frequency of Cardiac Contractions and Motor Movements in Subjects P-n and Pod-v During Prolonged Stay at Heights of 3000 (1), 5000 (2), and 7000 m (3).



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Figure 4. Critical Frequency of Flicker Fusion (1) and Time Differential Thresholds (2) in Subject P-n During Prolonged Stay in the Pressure Chamber at a Height of 3000 m.

Note: d = day and n = night.

In the case of subject P-v (Fig. 5), on the other hand, the sort of phasing is not observed. The critical frequency of flicker fusion and differential time thresholds during the entire period of his stay in the pressure chamber are lower.

This fact indicates, probably, a progressive reduction of function. The first subject followed daily regime no. 1, and the second, regime no. 2.

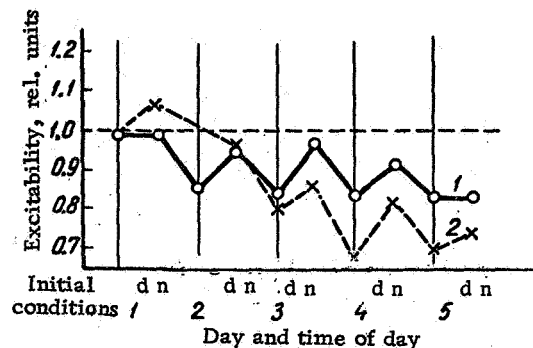


Figure 5. Critical Frequency of Flicker Fusion (1) and Time Differential Thresholds (2) in Subject P-v During Prolonged Stay in the Pressure Chamber at a Height m.

The data given provide a basis for assuming that in the latter case for subject P-v there was a progressive weakening of the simulation process. This is also indicated the deterioration in the general conditions of the subject, so that it was necessary to conclude the experiment on the fifth day. A similar picture was also observed in the case of subject D-v, who was also following regime No. 2 and who terminated the experiment on the 10th day. The information within the range studied (3000-7000 m) does not have a clearly defined influence on man. The functional changes in the organism depended considerably on the length of stay at the height.

Thus, in experiments involving a

30-day stay, a moderately pronounced but regularly increase in the pulse rate amounting to 10-15 beats per minute was observed beginning on the 14th or 15th day. This pulse rate either was maintained until the end of the experiment or continued to increase.

Data obtained from an orthostatic test also indicates increased excitability of the cardiovascular system in subjects during prolonged experiments. Thus, in the first 10-15 days of the stay in the pressure chamber the pulse rate for a given test increased by 10-35%, and during subsequent days, by 50%. At the same time there was a more pronounced increase in the arterial pressure as well. The changes noted were more pronounced in persons during wakefulness at night (regime No. 2). According to literature data, this kind of reaction indicates the onset of fatigue resulting from disturbances of the daily rhythm [3, 5, 6, 8].

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Disturbance of the relationship of stimulation and inhibition processes is also indicated by the data given earlier concerning certain visual functions and the variability of the delayed time reflex. The general direction of these changes tends toward a certain relative predominance of the stimulation process (increase in pulse rate and arterial pressure, increase pulse excitability in orthostatic tests, increased critical frequency of flicker fusion, etc.).

This trend of change is also indicated by a certain increase in the content of 17-oxycorticosteroids in the daytime urine and an increase in the albumina of the blood plasma (12%). The globulins, except for the α -globulins, usually decrease.

The changes mentioned above can be considered as possible indications of developing fatigue, resulting from incomplete functional restoration during the time devoted to rest through the day.

Since the subject followed different regimes of sleep and rest, it is of interest to consider separately the question of the nature of the changes in the daily rhythm of functions under the conditions of the experiment.

In the case of regime No. 1, which was the more usual regime, in most experiments the daily periodicity of functional changes (pulse frequency and breathing rate, arterial pressure, and body temperature) was quite clearly defined (Fig. 6). Minimum values were usually recorded during sleep at night, and maximum values during the day when the subject was awake.

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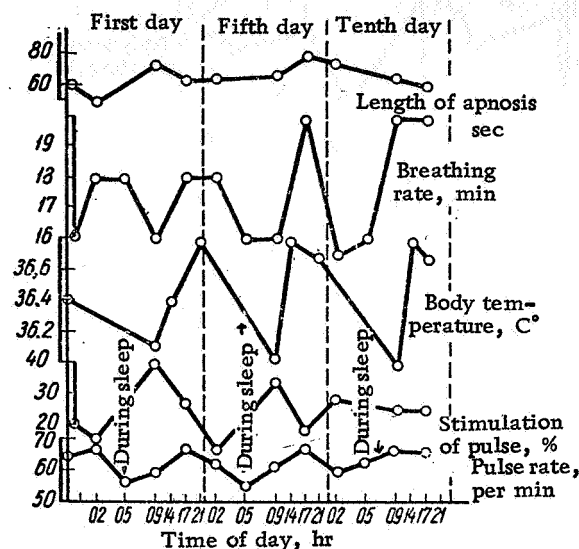


Figure 6. Daily Variations of Certain Physiological Indexes in Subject Pod-v on the Second, Fifth, and Tenth Days of the Experiment. Height 7000 m, Regime No. 1.

In the case of the other less favorable regime (No. 2) the daily periodicity of the functions studied was not so smooth, but often was even distorted (Fig. 7). Thus, for example, in the case of subject P-v the pulse frequency and breathing rate and body temperature were often greater during sleep than during wakefulness.

Daily periodic fluctuations in the EEG were observed in subjects following both regime No. 1 and regime No. 2. α and β rhythms were quite pronounced during wakefulness in the daytime. The α rhythm was regularly intensified when the eyes were closed. The frequency of the α rhythm was quite clearly defined for every subject during wakefulness. The slow EEG rhythms δ and θ were regularly observed during wakefulness (Fig. 8). But because of the masking effect of the higher frequencies, the slow rhythms were difficult to analyze visually, and this could only be done by special frequency analysis.

The total EMF of the EEG and the EMF of the frequency spectra for every subject were quite constant at a particular time of day. Minimum EMF of the EEG was usually observed in the morning, and maximum at night during sleep.

It is interesting to note that in the case of regime No. 2 the EEG recorded during wakefulness at night showed a shift of the dominant frequency toward slower variations.

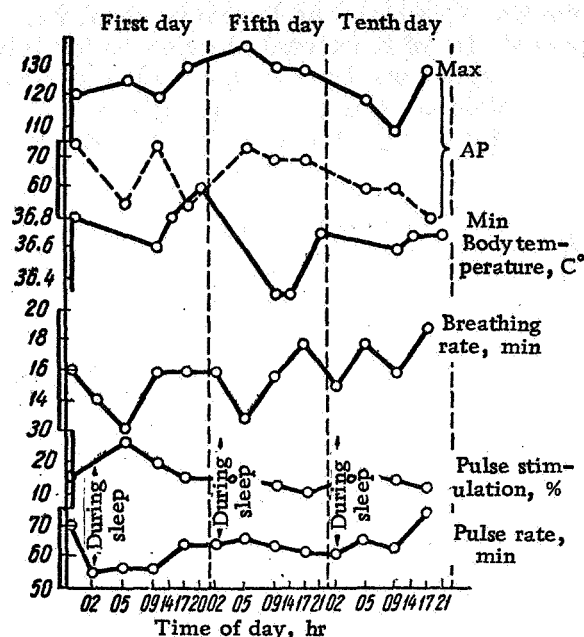


Figure 7. Daily Variations of Certain Physiological Indexes in Subject P-v. Height 5000
Regime No. 2.

The studies carried out show that a change in the ordinary daily regime involves a disturbance of the normal daily periodicity of physiological processes. The practical significance of this fact, which was also noted previously under other experimental conditions [1, 2, 7] means that special studies must be carried out to find appropriate regimes of sleep and wakefulness for crews of spaceships. In this regard it should be emphasized that more than just the length of time devoted to sleep must be taken into account for proper choice of the best regime. Experimental information available thus far indicate that wakefulness during the night (from 3 to 6 hr), i. e., during the usual daily period of deepest sleep, has a deleterious effect on capacity for work.

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We still have absolutely no experimental information on the role of interoceptive and proprioceptive impulses, and their relationship to gravitational forces. The condition of weightlessness evidently can have a substantial influence on the dynamics of fundamental nervous processes, and these in the last analysis also determine the periodic character of changes in the functional state of the organism, including the succession of periods of sleep and wakefulness.

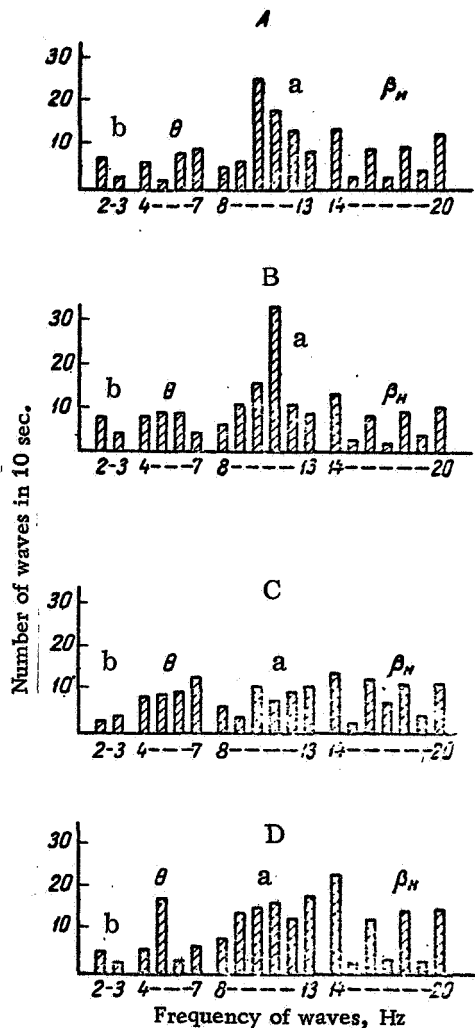


Figure 8. EEG Spectrogram of Subject F-k (Regime No. 2) as Recorded at 10 AM (A), 2 PM (B), 1 AM During Sleep (C), and 5 AM During the Time of Nocturnal Wakefulness (D).

sure chamber a slight increase was observed in the latent period (4-20 sigmas) and amplitude of the patellar reflex. The magnitude of the static reflexes (cephalogram) increased (from 3 to 8 mm). Unconditioned vascular reflexes during the after effect period increased in some cases, decreased in other cases, and sometimes were reversed. These variations were not found to depend on the degree of rarefaction and the length of stay in the pressure chamber.

The gas exchange of the subjects merits study in order to evaluate the conditions of the experiment—the degree of rarefaction and the length of stay. Studies conducted in this regard have shown that prolonged stay in a pressure chamber is accompanied by a decrease of 20% or more in the gas exchange of the subjects as compared with the initial value. The reduction in gas exchange was more pronounced in persons following regime No. 1, and it did not depend on the degree of rarefaction in the pressure chamber. The significant reduction in the total activity of the subjects can be considered as the very probable cause of the reduction in gas exchange.

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Protein, fat, and carbohydrate metabolism studied during the experiment did not vary appreciably. Somewhat different data were obtained on the cholesterol metabolism. In the experiment carried out at heights of 5000-7000 m, the cholesterol content of the blood increased 100-150 mg % on the eighth day of the stay in the pressure chamber. More detailed data concerning changes in metabolic processes will be given in special communications.

Several changes worthy of attention were observed as a result of clinical examination of persons participating in the experiment.

Even during the sojourn in the pres-

Phenomena of hypertonia were often observed in the persons examined during the aftereffect period: maximum arterial pressure dropped to 90 mm Hg, and minimum to 35-40 mm Hg.

Study of arterial pressure, systolic and cardiac output, and the rate of propagation of the pulse under conditions of rest and exertion indicate some loss of conditioning of the cardiovascular system which was more clearly evident after the 30-day experiment.

This probably also is to be explained by the prolonged limitation of movement of the subject. Hence we are faced with the need for developing a special set of physical exercises to maintain overall functional tone of the organism at sufficiently high level during the time a man remains under conditions which restrict his overall activity and movement [4].

Phenomena related to loss of functional tone were less pronounced in persons who participated repeatedly in prolonged experiment. This gives us reason to suppose that special training is desirable for situations of this sort.

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Our studies also showed that the personality characteristics of the subjects are not the least important factor to be considered in setting up experiments involving prolonged stay of several subjects in a small chamber.

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EFFECT OF ADAPTATION TO HIGH MOUNTAIN CONDITIONS ON HUMAN RESISTANCE TO ACUTE HYPOXIA AND HIGH TEMPERATURE

V. B. Malkin and G. D. Yukhnovskiy

Acclimatization to high mountain conditions, an essential element of which is adaptation to existence under conditions of a lowered partial pressure of oxygen in the inspired air, is regarded by many investigators as an effective method of increasing the adaptation reserves of the body [1, 3, 4, 6].

Investigations on animals have shown that after a long stay at a lowered barometric pressure animals are more resistant to any action of many unfavorable external environmental factors: an acute deficiency of oxygen in the inspired air, a high temperature, increased gravitational force, ionizing radiation, etc.

Most clinically healthy persons, after a relatively long stay in the mountains at an altitude of the order of 2000-7000 m, are more resistant for a certain length of time to the action of acute hypoxia than healthy persons who are not altitude trained [2, 3, 5].

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It has also been found that daily training for 1 month in a pressure chamber at an "altitude" of 6000 m not only increases the altitude resistance of clinically healthy persons, but also increases their resistance to the action of high and low temperature [6].

The object of this investigation was to study the effect of adaptation to high mountain conditions on the resistance of healthy persons to the action of acute hypoxic hypoxia and to the action of a high external environmental temperature.

We were interested in whether it is possible and desirable to use adaptation to high mountain conditions as a method of increasing man's resistance to various experimental factors of flight.

METHOD

The investigation was carried out with different groups of clinically healthy persons: 11 highly skilled athletes, 10 physically well-developed young men not previously living in the mountains, and the 5 research workers taking part in the present investigation.

In 1964, five healthy men were adapted to high mountain conditions in stages: 12 days at an altitude of 2000 m (Terskol); 12 days at 3800 and 4200 m ("Ledovaya Baza" and "Refuge II") and 5 days at an altitude of 2000 m again. In 1965 the length of stay at an altitude of 3800-4200 m of the same group of subjects was lengthened to 20 days.

The mountaineers stayed for 6 days at an altitude of 2000 m (Tereskol), and then completed their ascent.

The research worker group spent most of their time for 25-28 days at an altitude of 2000 m (Terskol), but periodically in connection with their work they climbed to "Ledovaya Baza" and for a short time to "Refuge II." Including overnight stays, each worker spent from 4 to 6 days at "Ledovaya Baza."

High-altitude experiments. Before and after their stay in the mountains the members of the expedition had their resistance to high altitudes determined. Under pressure chamber conditions, the subjects were raised in stages, without oxygen, to a high altitude until they began to show clear signs of profound hypoxia, such as gross disturbances of writing, inability to solve elementary arithmetical problems, clonic spasms of the writing hand (writer's cramp), and disturbances of consciousness of different degrees.

In the first experiments with five subjects the altitude up to which the pressure chamber was "raised" before and after their stay in the mountains did not exceed 7000 m, and only the length of their stay at this altitude was considered. In all the other experiments the pattern of the ascent was as follows. Up to an altitude of 5000 m at a speed of 25 m/sec, with a pause of 15-20 sec or thereabouts every kilometer, starting from an altitude of 5000 m a pause of 5 min at each successive altitude.

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Before, during and after completion of the ascent recordings were made of the following in all subjects: the electroencephalogram (EEG) in the fronto-occipital lead, the electrocardiogram (ECG) in three standard leads, the respiratory movements of the chest wall, and (periodically) the arterial pressure and the oxygen saturation of the arterial blood. Throughout the experiment continuous observations were kept on the subject's behavior and general condition.

To assess his working capacity and intellectual activity, during his stay at a high altitude the subject was given arithmetical problems to solve (multiplication of double-figure numbers).

HEAT EXPERIMENTS

Altogether 24 high-temperature experiments were carried out in a combined heat- and pressure-chamber at normal barometric pressure and at an environmental temperature of +70° (temperature of chamber walls between +90 and +92°), the relative humidity being 40%.

The subjects wore shorts and sat in the armchair provided in the chamber. No ventilation was present in the chamber.

In the course of the experiments the subjects were kept under continuous medical observation and two-way radio communication was maintained. Every 10 min recordings were made of the ECG in lead II, the respiratory movements of the chest wall, and the body temperature by means of an alcohol thermometer under the tongue. By weighing the subjects on medical scales before and at the end of the experiment the loss of moisture could be determined.

The subject's general condition was assessed from how they felt subjectively and from their temperature sensation.

RESULTS

A distinct increase in resistance to high altitudes was found in 5 subjects taking part in the first expedition after their stay in the mountains.

Four subjects spent a period of 20-30 min without oxygen at an "altitude" of 7000 m after their return from the mountains, and during this time their general condition remained perfectly satisfactory and their ability to work continued at a high level.

Interesting results were obtained by investigation of subject P-is, whose ECG taken before his trip to the mountains, after physical exertion (20 knee-bendings in 40 sec), during rotation on a centrifuge, and also during ascent in the pressure chamber revealed ventricular extrasystoles, increasing in intensity with an increase in load. Their appearance made it necessary to terminate the investigation at an altitude of 5000 m after only 3 min to keep the subject's general condition satisfactory. After a stay in the mountains, including ascent of the eastern summit of El'brus, no cardiac arrhythmias were found in the examination of this subject in the pressure chamber in the course of a 30-minute stay at 3000 m, and he tolerated the high-altitude experiment well. The remaining subjects remained in the pressure chamber for between 1 and 9 min only, when taken to an altitude of 7000 m before their trip to the mountains.

In subsequent experiments we made a few modifications to the technique of determining resistance to high altitudes so that the results of experiments with different groups of subjects could be compared.

As our earlier investigation (V.B. Malkin, N.M. Asyamolova and A.K. Kochetov) showed, mountaineers possess high resistance to altitude and, as a rule, they feel well at an altitude of 7000 m for a long time; for that reason, when investigating this group of subjects, it was essential to take them up to higher altitudes in order to determine their altitude resistance.

Data for the altitude resistance of the three different groups of subjects before and after a stay in the high mountains are given in the table.

In the case of young men going to the mountains for the first time, feeling fit while they were there, and successfully climbing to the eastern summit of El'brus, their stay in the mountains led to an appreciable (in 3 of 5) increase in altitude resistance. The resistance of one subject, who suffered from mountain sickness, fell slightly and that of another, whose initial background resistance was high, increased relatively slightly.

The changes in altitude resistance of the mountaineers were slight: in 4 the resistance was practically unchanged (a change of less than 30 sec), in one it fell and in 6 it increased. However, in 2 of these 6 subjects the increase was due to the fact that their background resistance was lower than in the previous experiments with the same subjects.

A significant increase in resistance in this group was in fact obtained with only 3 subjects, two of whom went to the mountains after a relatively long interval. This was evidently the cause of the lower background resistance of these subjects.

We attempted to find a relationship between the adaptation regime in the mountains and the altitude resistance of the mountaineers. No increase in altitude resistance was found in two mountaineers (Ts-n and K-ov), who had the greatest load and stayed at altitudes of the order of 4000-4800 m for longer than the others: in one it fell and in the other it remained substantially unchanged.

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TABLE. Changes in Altitude Resistance Before and After a Stay in the Mountains

Surname	Before stay in mountains		After mountains on 4th-6th day		After mountains, on 28th-32nd day		Changes in resistance
	alti- tude, km	time, sec	alti- tude, km	time, sec	alti- tude, km	time, sec	
Subjects							
A=ev	9	120	8	300	8	300	Lowered
V=ko	9	190	9	60	8	300	Raised
K=as	7	300	8	2700	8	220	The same
Sh=k	8	90	9	70	—	—	The same
K=us	9	50	9	140	9	100	The same
Mountaineers							
Ts=n	8	240	8	240			Unchanged
K=ov	9	110	8	300			Lowered
K=in	9	70	9	200			Raised
K=ev	9	110	9	130			Unchanged
T=m	8	120	9	165			Raised
S=t	9	160	9	140			Unchanged
B=ov	9	40	9	120			Raised
N=ov	8	90	8	250			The same
G=r	8	300	9	100			The same
B=d	9	40	9	130			The same
M=n	9	70	9	60			Unchanged
Research workers							
U=a	8	80	8	270			Raised
R=a	7	70	8	150			The same
L=a	7	90	8	120			The same
M=ko	6	300	7	110			The same
M=ns	5	270	5	300			Unchanged

I consider that it would be premature to attribute these results to excessive physical exertion, for some increase in altitude resistance was observed among

the mountaineers, including among those who took part in an expedition to the Tyan'-Shan' (Khantengri district), making a difficult climb with a heavy load and staying for a relatively long time at altitudes of 6000-7000 m.

Three of the 5 research workers showed a distinct increase in altitude resistance after a stay in the mountains, one showed a very slight increase, and the remaining one, with low resistance, showed no change. This last case (M-is) merits special attention, because when this subject was taken up in the pressure chamber to an altitude of 5000 m before making his trip to the mountains, he unexpectedly developed bradycardia, lost consciousness, and had a fit. While in the mountains, M-is worked at altitudes of 3800-4200 m and felt perfectly fit, although after staying 5 min at an altitude of 5000 m he again developed severe bradycardia and a state of precollapse.

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We were concerned above all to discover the causes of the marked increase in altitude resistance arising in some cases after adaptation in the mountains.

Analysis of the results of recording the physiological parameters showed that the respiration of these subjects was intensified to the greatest degree at a high altitude, as a result of which the oxygen saturation of their arterial blood was considerably higher during elevation to a high altitude in the pressure chamber after a stay in the mountains than during the control elevation (Fig. 1).

This factor also probably determined the changes in higher nervous activity of the subjects and in the bioelectrical activity of their brain. After returning from the mountains they were able to remain capable of working, with a relatively unchanged EEG, for longer then before their stay in the mountains.

Very strikingly, the oxygen saturation of the arterial blood of the subjects showing an increase in altitude resistance either was the same as in the control investigation at the moment of completion of the altitude test or, in a few cases, it was actually a little higher. These findings demonstrate that a stay in the mountains (adaptation to chronic hypoxia) does not enable the body to maintain a sufficiently high level of ability to work under the conditions of a reduced oxygen supply, but is accompanied by a more efficient and more precisely adjusted activity of its functional systems responsible for the transport of oxygen to tissue structures most sensitive to hypoxia.

The fact that different groups of subjects showed different changes in altitude resistance is probably connected to some extent also with differences in the course of the acclimatization process itself, clearest evidence of which is provided by the decrease in altitude resistance of subject A-ev, who suffered from mountain sickness, and also by the results of the hematologic tests (I.A. Roshchina). Blood tests performed on the group of young men visiting the mountains for the first time showed a definite increase in hemoglobin concentration and erythrocyte count, corresponding to the altitude to which they climbed; the same response, but less marked, was also found among the research workers, whereas among the mountaineers it was hardly noticeable.

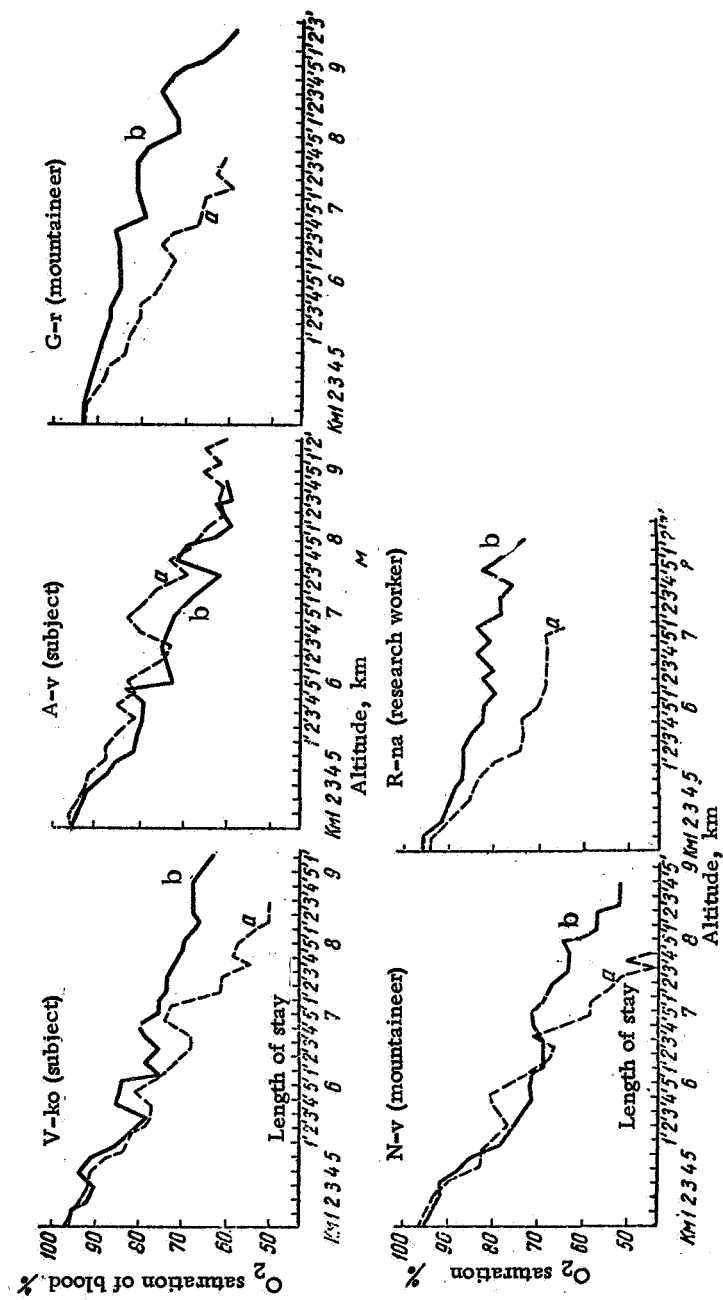


Figure 1. Changes in Oxygen Saturation of Arterial Blood During Elevation in a Pressure Chamber Before (a) and After (b) a Stay in the Mountains.

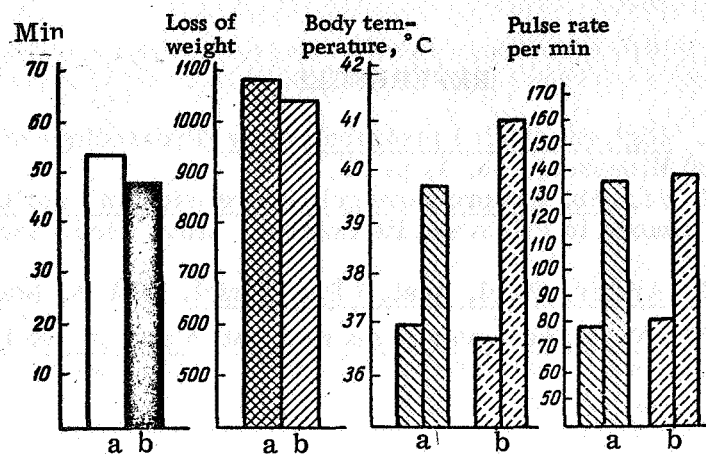


Figure 2. Length of Stay in Hot Chamber at a Temperature of $+7^{\circ}$, Together With Change in Weight, Body Temperature and Pulse Rate Before (a) and After (b) a Stay in the Mountains (Mean Data for 11 Persons).

A fact of definite practical interest is that the increase in altitude resistance, like the resistance to the action of radial acceleration, persists for a month or even longer after high-mountain adaptation.

The results of our high-temperature experiments were somewhat unexpected. /287 We had considered that a stay in the mountains would lead to an increase in the subjects' resistance to a high temperature. Moreover, in experiments performed jointly with F. V. Babchinskiy on animals, a significant increase in the survival rats of mice adapted in the mountains was observed at a temperature of $+60^{\circ}$.

The results given in Fig. 2 show that the resistance of most of the subjects to a high temperature 10-14 days after their return from the mountains showed a slight decrease. It is important to note that the rise of body temperature, the main criterion of the reaction of the body to overheating, took place appreciably faster in nearly all the subjects after their stay in the mountains than in the control experiments.

After their return from the mountains the subjects' general condition toward the end of their stay in the hot chamber was appreciably worse than in the control experiments. This explained why two subjects after adaptation in the mountains were in a state of precollapse when the experiment was stopped, whereas all the control experiments were stopped at the subjects' request, because they had begun to feel unpleasant effects from the heat. The impression was thus created that, although after adaptation to high mountain conditions the subjects were able to endure a higher increase of body temperature, their resistance was nevertheless slightly lowered.

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ADAPTATION TO HYPOXIA AS A MEANS OF INCREASING HUMAN RESISTANCE TO RADIAL ACCELERATION

A. R. Kotovskaya, P. V. Vasil'yev, R. A. Vartbaronov, and S. F. Simpura

Among the measures increasing human resistance to overloads an important place is held by physiological methods increasing the reserve powers of the body. These include preliminary physical training, training on a centrifuge, administration of drugs, etc. The specific method of increasing resistance (training on a centrifuge) should probably be used with care, because observations have been reported indicating the development of prolonged functional disturbances and morphological changes under the influence of radial accelerations [3, 6-9, 13].

At the present time researchers are showing great interest in methods of physical training and adaptation to hypoxia as a means of increasing bodily resistance to the action of various injurious external environmental factors [1, 5, 11, 12, 16, 17].

Assuming that hypoxia plays a leading role in the pathogenesis of the disturbances developing during the action of overloading, in conjunction with V. P. Dudarev [4] we carried out experiments on animals to study the effect of adaptation to a lowered partial pressure of oxygen and of muscle training on their resistance to overloads. These experiments showed that adapted albino mice and rats and guinea pigs have much greater resistance than control animals. The results of these experiments justified moving on to investigations on man.

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The object of the present investigation was to study the effect of repeated and primary acclimatization in the mountains on the level of tolerance to radial acceleration and also to examine the features distinguishing nonspecific adaptation processes.

Investigations were conducted on 15 subjects, 7 of whom were mountaineers with more than 10 years of experience of the sport. All subjects lived in high mountain conditions at altitudes of between 2-3 and 4-7 km in succession in the region of Mt. El'brus, and two mountaineers lived in the Tyan' Shan' mountains.

The length of stay in the mountains varied from 35 to 41 days for the mountaineers and from 33 to 35 days for the persons adapted for the first time.

The limit of tolerance to radial acceleration was determined by rotation on a centrifuge with an arm radius 7.5 m. The gradient of increase of acceleration was 0.1 g/sec up to 4 g, and 0.2 g/sec thereafter; the angle of inclination of the back of the armchair was 65° to the acceleration vector.

The criterion of limit of tolerance which was most frequently used was the appearance of visual disturbances in the form of a "black" or "gray veil," and less commonly, of disturbances of the circulatory or respiratory indices. Each subject's resistance to acceleration was measured not less than 1-2 weeks before acclimatization and 10-15 days and 1.5-3 months after a stay in the mountains.

The following tests were used to assess the physiological responses to acceleration: the ECG was recorded in three leads by Nebb's method, the arterial pressure measured in the vessels of the arm and ear, and the respiration rate and volume recorded [15]; the time of the motor response to a photic stimulus was determined; the visual acuity was measured.

Two-way radio communication was maintained during the experiments and continuous visual observation of the subject was undertaken by television. The results of the investigations showed that the maximal acceleration tolerated by unadapted persons in the control tests was 0.8 g less than that tolerated by the mountaineers.

After a stay of 33-40 days under high mountain conditions both the mountaineers and the unadapted persons showed a significant increase in resistance to acceleration (Table). Tolerance was increased in all the mountaineers without exception, on the average by 1.7 units (within a range of 0.6 to 2.8 units).

The changes in resistance of the subjects adapted for the first time to acceleration showed greater individual scatter.

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TABLE. Mean Values of Maximal Tolerated Accelerations Before and After Acclimatization in the Mountains

Groups of subjects	Number of cases	Mean values of maximal tolerated accelerations, g			P <
		Before acclimatization	After acclimatization	Difference	
Mountaineers Subjects adapted for the first time	7	10.3±1.4	12.0±1.1	+1.7±0.6	0.001
	8	9.6±0.7	11.2±1.3	+1.6±1.4	0.05
	6	9.4±0.6*	11.6±1.0*	+2.2±1.0	0.01

Sampling Mean for Subjects Adapted for the First Time and Showing an Increase in Resistance to Accelerations.

The increase in resistance to acceleration after adaptation under high mountain conditions is also confirmed by changes in some physiological indices especially those characterizing visual function. The threshold of the "gray

veil" was raised by 1.9 ± 0.7 g in the mountaineers and by 2.6 ± 0.8 g in the unacclimatized subjects after a stay in the mountains. Only in two cases was the threshold of appearance of visual disturbances slightly lowered after acclimatization (Fig. 1). In addition, after adaptation to hypoxia, in 10 of 14 cases a higher visual acuity was found than in control subjects exposed to accelerations of identical magnitude.

Nonspecific adaptation processes can be assessed by analyzing changes in certain physiological responses to acceleration before and after adaptation to hypoxia. The mean pulse rate during control rotation at radial accelerations of 8 g was 132 ± 14 beats/min for the mountaineers and 118 ± 14 beats/min for subjects adapted for the first time.

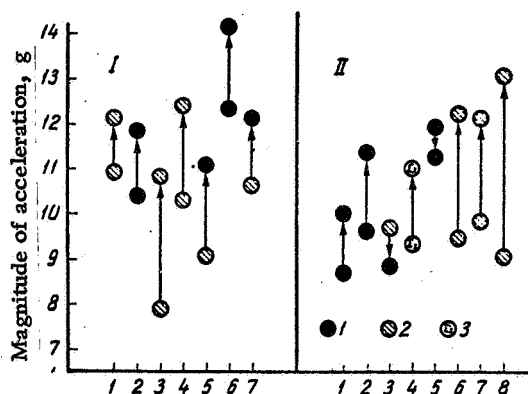


Figure 1. Change in Level of Tolerance and in Severity of Visual Disturbances in (I) Mountaineers and (II) Persons adapted for the First Time After a Stay in the High Mountains. 1) Black Veil, 2) Gray Veil, 3) Extrasystoles.

After acclimatization in the mountains in most cases a more marked tachycardia was observed at accelerations of the same magnitude. The difference in pulse rate for all subjects averaged $+12 \pm 12$ beats/min ($P < 0.05$). In four cases, however, opposite relationships were observed: the increase in pulse rate was less after acclimatization.

Comparison of the indices of external respiration corresponding to identical magnitudes of acceleration showed that the respiration rate remained at about the same level during acceleration of the centrifuge after the subjects had returned from their stay in the mountains as in the control test. The mean difference in the respiration rate was 1-2 cycles (within the range of -4 and +8 cycles/min). The changes in pulmonary ventilation and

gas exchange were typical in character of exposure to the action of radial acceleration. After mountain acclimatization, the pulmonary ventilation in most cases, and the oxygen consumption in every case, were at a higher level during acceleration of the centrifuge than in the control tests.

In the braking period and immediately after stopping the centrifuge signs of stimulation of respiration were observed, as a result of the oxygen deficit arising during exposure to acceleration. After adaptation to hypoxia, the severity of these changes varied from one individual to another. Despite the considerable magnitude of the overloading reached during braking, in half of the cases the oxygen consumption was practically indistinguishable from the background level or was actually slightly below it. In most cases the oxygen debt was smaller after adaptation than after the background test. Even in cases when no increase in tolerance to overloading took place (2 subjects), the oxygen consumption and oxygen debt during braking and after stopping the centrifuge were

lower than in the first test, demonstrating an increase in the body's reserve powers after adaptation in hypoxia. The respiratory quotient remained higher after adaptation in the mountains than in the control rotations (Fig. 2). The simultaneous increase in the oxygen consumption and respiratory quotient could evidently be attributed to the increased powers of the body to maintain oxygen utilization at a higher level.

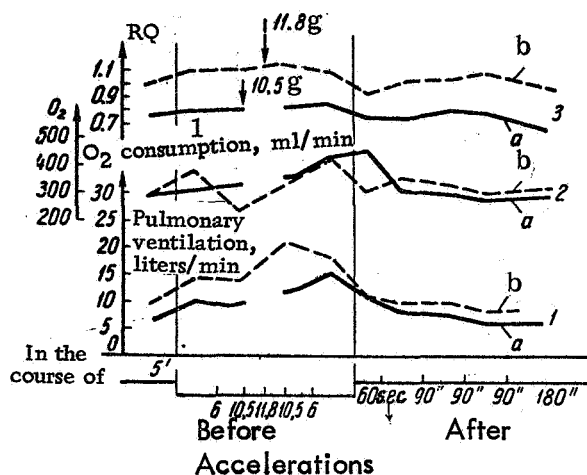


Figure 2. Changes in Pulmonary Ventilation (1), Oxygen Consumption (2) and Respiratory Quotient (3) in the Mountaineer S-t During Exposure to Accelerations before (a) and After (b) a Stay in the High Mountains. Total Duration of Spinning 510 sec.

It may be concluded from the results described above that a short stay under high mountain conditions is an effective and reliable method of

increasing human resistance to accelerations. By comparing certain physiological responses preliminary views can be expressed on the possible mechanisms of this adaptation. The strengthening of activity of the cardiovascular and respiratory systems and the response to overloading should probably be regarded as an adaptive response of the human body connected with increased utilization of oxygen in the tissues. On the other hand, another possible cause cannot be ignored: an increase in the resistance to the blood flow because of a possible increase in the viscosity of the blood after a stay under hypoxic conditions. We made no direct measurements of the blood viscosity of our subjects. However, cases of an increase in the blood viscosity of animals in the course of acclimatization to high altitudes have been described in the literature [14].

The results thus demonstrate the need for a further study of the mechanisms of nonspecific adaptation as applied to the problem of human resistance to the action of overloads.

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CONTINUATION OF INVESTIGATIONS OF CHANGES IN OSMOTIC
RESISTANCE OF ERYTHROCYTES DURING ACCLIMATIZATION
TO HIGH MOUNTAIN CONDITIONS

Z.I. Barbashova

In an expedition undertaken in 1964 we found that phasic changes take place in the osmotic resistance of the erythrocytes (ORE) in the blood of man and animals. We were particularly interested in the fact that the increase in ORE observed in the first days after returning from the mountains to sea level correlated with an increased resistance of human subjects and animals to acute hypoxia in a pressure chamber and to spinning. Since the number of human subjects investigated was too small (5 persons), it was necessary to obtain more precise data by means of a second expedition, during which attempts could be made to discover the mechanisms of the changes in resistance of the erythrocytes.

The investigation described below was also conducted on human subjects, under the same conditions of acclimatization to mountain conditions as in the 1964 expedition. Altogether 26 persons were investigated: 5 men undergoing acclimatization in the mountains for the first time (Group 1; ages 20-24 years), 11 first-class mountaineers, with the rank of Master of Sport (Group 2, ages 32-40 years), and 10 young athletes (Group 3, ages 16-17 years). The acclimatization carried out with all the persons of these three groups was active, i. e., it entailed considerable physical exertion and climbs to various altitudes. However, the common program for the different groups was identical only for the first 7-10 days (when they rested at an altitude of 2000 m). After the rest, the mountaineers made climbs which were not particularly high (not above 4500 m) but were of the greatest difficulty. For resting, they came down to an altitude of about 2000 m. The subjects of Group 1 made trips to increasing altitudes: they climbed to "Refuge Eleven" (4200 m), to "Pastukhov Refuge" (4500 m) and, finally, to the summit of Mt. El'brus (5635 m). For resting they descended to "Ledovaya Baza" (Ice Base), at 3800 m. The group of young athletes (6 youths and 4 girls) stayed all the time at Terskol (2000 m), but carried out intensive athletic training with periodic short climbs to altitudes not exceeding 3800 m.

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As a rule the ORE was determined on the same day as blood was taken for total blood count, which was carried out by N. V. Roshchina, Ye. B. Gippenreyter and myself. Blood was taken from the finger and diluted to a certain degree in tubes with NaCl solutions of decreasing concentration. The degree of hemolysis was estimated colorimetrically and expressed as a percentage relative to the sample in which the erythrocytes were hemolyzed completely. Most subjects were tested 6 times: in Moscow before setting off for the mountains (initial data at sea level), on the 1st and 2nd days after arrival at Terskol (2000 m), 9-10 and 19-20 days later, at the end of the stay just before departure (28-30 days later), and 5-6 days after coming down from the mountains, i. e., in the first days of life at sea level in Moscow.

RESULTS

It will first be noticed that the initial values of the normal ORE for all the men investigated were very similar (table). The four girl athletes (Group 3)

TABLE. ORE of Subjects During Their Stay in the Mountains.

Concentration	Groups of subjects			
	1	2	Youths	3 Girls
Initial data (Moscow)				
	(5)*	(2)	(6)	(4)
0.60	9.0±4.94	0	5.3±1.93	14.2±4.11
0.56	27.8±5.36	23.0	21.6±3.22	52.0±8.31
0.52	53.6±7.43	48.5	44.5±3.52	75.0±4.31
0.48	79.2±3.18	87.5	79.3±5.01	89.2±1.01
for 50% hemolysis	0.528±0.010	0.52	0.513±0.002	0.56±0.008
1-2 days in mountains (2000 m)				
	(5)	(10)	(6)	(4)
0.60	0.6±0.6	1.5±0.53	0.17±0.05	2.0±1.06
0.56	3.6±1.94	5.3±1.29	2.5±1.06	5.8±1.80
0.52	16.8±3.24	21.9±3.16	28.2±2.41	30.0±6.27
0.48	52.4±7.33	56.3±5.03	65.0±5.36	77.8±4.09
for 50% hemolysis	0.48±0.006	0.485±0.005	0.495±0.003	0.51±0.036
p	<0.02	<0.001	<0.01	<0.01
8-9 days in mountains				
	(5)		(6)	(4)
0.60	5.0±0.63		1.0±1.0	3.7±2.17
0.56	14.2±2.32		14.8±4.35	16.2±3.68
0.52	56.2±5.48		50.5±7.73	61.7±5.97
0.48	85.0±2.21		85.3±2.79	89.5±1.94
for 50% hemolysis	0.524±0.004		0.52±0.006	0.534±0.004
p	>0.5		>0.5	=0.02
19-20 days in mountains				
	(5)		(6)	(4)
0.60	3.0±1.04		6.1±2.83	5.8±1.93
0.56	25.4±3.14		30.7±6.94	25.3±1.70
0.52	66.6±7.86		75.9±3.72	69.3±5.51
0.48	90.6±3.78		93.0±2.11	89.0±1.58
for 50% hemolysis	0.532±0.006		0.545±0.006	0.538±0.03
p	>0.5		<0.02	<0.05

TABLE (Continued)

Concentration	Groups of subjects			
	1	2	Youths	3 Girls
28-30 days in mountains				
	(5)	(8)	(6)	(4)
0.60	3.4 ± 1.42	0.0 ± 0	2.0 ± 1.11	1.8 ± 0.85
0.56	16.8 ± 4.07	6.1 ± 1.08	8.8 ± 3.65	8.3 ± 1.38
0.52	48.4 ± 4.97	42.9 ± 2.65	41.0 ± 6.91	43.8 ± 6.06
0.48	81.2 ± 2.52	79.6 ± 2.10	80.3 ± 3.82	77.5 ± 3.12
for 50% hemolysis	0.516 ± 0.004	0.51 ± 0.008	0.515 ± 0.008	0.515 ± 0.003
P	> 0.25	> 0.05	> 0.5	< 0.01
5-6 days after descent from mountains				
	(5)		(5)	(4)
0.60	0.3 ± 0.24		3.6 ± 1.50	3.5 ± 1.55
0.56	0.8 ± 0.75		26.4 ± 8.08	22.0 ± 3.65
0.52	23.8 ± 5.12		51.4 ± 11.27	65.5 ± 5.01
0.48	70.0 ± 5.64		80.8 ± 6.84	8.88 ± 4.00
for 50% hemolysis	0.495 ± 0.003		0.522 ± 0.01	0.53 ± 0.006
P	< 0.02		> 0.5	< 0.05

Number of subjects given in parentheses

showed a lower osmotic resistance of their erythrocytes to identical concentrations of NaCl in solution. In all persons of Group 1, for instance, 50% hemolysis of erythrocytes took place in a salt concentration of $0.528 \pm 0.010\%$, in two mountaineers (Ku-v and Gip-r) in 0.52% NaCl (unfortunately initial data were not obtained for the other mountaineers), in the young male athletes in $0.513 \pm 0.002\%$ NaCl, but 50% hemolysis of the girls' erythrocytes took place in $0.56 \pm 0.008\%$ NaCl, i. e., in a less hypotonic salt solution.

On the 1st and 2nd days after their arrival in the mountains the ORE of 25 of the 26 subjects was considerably raised. The zone of NaCl concentrations within which 50% hemolysis now took place was entirely shifted to the right, i. e., toward the lower values. These values were 0.48, 0.48, 0.49 and 0.51% respectively. As a rule the hemolysis curves were similar for the subjects of all groups tested. The ORE was not raised in one mountaineer (Gip-r) only, and immediately after arriving in the mountains he was very busy with the work of organizing the research in the expedition camp, entailing considerable physical and emotional stress. In fact, his ORE fell slightly, and because of this his data were not used when calculating the mean values for the group of mountaineers. /296

The changes in ORE at subsequent times of investigation in the mountains were physic in character and did not always coincide in the various subjects. As

a rule the hemolysis curves showed normalization, returning to their original values. Only in 3 of the 4 girls did the ORE remain raised throughout the month of their stay in the mountains. The normal ORE values were restored in the fourth girl (Mak-va). This girl was not as fit as the others, she developed tonsillitis while in the mountains, and she did not tolerate her stay in the mountains very well, as was noted in particular when she climbed to 3800 m.

After coming down from the mountains, during the first days of life in Moscow, the subjects showed a raised ORE: in all persons of Group 1 (just as with the 1964 expedition), in the girl athletes (except Mak-va) and in 2 of the 6 mountaineers investigated (in Gro-va and Ni-v). The ORE of two other mountaineers (Ku-v and Gip-r) remained within normal limits. Finally, the ORE of two mountaineers (B-n and Ts-n), who came down from the mountains long before the others, was very low. Unfortunately we did not have the original hemolysis curves for these mountaineers and the comparison had to be made with the original data for all the adult men, including the mountaineers Ku-v and Gip-r. The ORE curves for the young male athletes remained within normal limits.

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Comparison of the changes in osmotic resistance of the erythrocytes with the general resistance of the subjects revealed the following pattern. Tests of general resistance of the men of Group 1 again confirmed the beneficial action of active acclimatization in the mountains. After returning from the mountains, their resistance to acute hypoxia in the pressure chamber (V. B. Malkin and co-workers) and to spinning on a centrifuge (P. V. Vasil'yev and co-workers) was considerably increased. As I stated above, their ORE was raised, confirming our previous findings of a direct correlation between the resistance of the body as a whole and the ORE. However, this applied to only 4 of the 5 subjects of Group 1. The general resistance of one of them (Al-v) to laboratory tests was not raised, but lowered, although the ORE was raised as in the other four subjects. In the case of Al-v, in the period of his stay in the mountains bleeding from the nose occurred frequently. He was a little more anemic and appreciably weaker than the rest. However, the dynamics of the changes in ORE were the same for him as for the others. In this case we cannot therefore speak of a correlation between the general resistance and the osmotic resistance of the erythrocytes.

In the group of mountaineers this correlation likewise was not found in every case. Both the general resistance to laboratory tests and the ORE of mountaineer Ni-v were raised. In Ku-v and Ts-n the resistance to acute hypoxia was practically unchanged. The ORE likewise was unchanged. However, there were exceptions. The mountaineer Gip-r, for example, showed greatly increased resistance to laboratory tests, but his ORE not only was not higher than initially, but was actually a little lower.

Unfortunately no laboratory tests were performed on the young athletes. Some idea of their general resistance could be obtained only from the results of athletic competitions in which the youths and girls took part soon after returning from the mountains. Good results were obtained by 3 of the 4 girls, those whose ORE was raised. The fourth (Mak-va), on the other hand, was in poor athletic form. She was the only subject not to have a raised ORE. These comparisons suggest the presence of a direct correlation between the general resistance of

the body and the ORE. Differences between the young men and girls, on the one /298
hand, and the adults on the other, were observed in a number of aspects of their
response to residence and to physical training in the mountains. The young sub-
jects lost weight considerably, and nearly all were affected to some degree by
upper respiratory tract infections. This must be a warning to trainers preparing
training programs under mountain conditions. They also differed from the adults
in the changes in their ORE, as was mentioned above.

Hence, when comparing the resistance of the body as a whole with the os-
motic resistance of the erythrocytes, we must recognize that there was a direct
correlation between these indices in 14 of 17 cases. In three subjects there was
none. However, with certain reservations, the ORE can be used as a test of
successful acclimatization and of the general resistance of the body.

EFFECT OF HYPEROXIA ON DYNAMICS OF ERYTHROPOIESIS IN ANIMALS

A. M. Shmeleva and I. S. Breslav

The response of the red blood (the erythron) acquires especial significance when an animal lives in an atmosphere with a modified partial pressure of oxygen.

Most workers who have studied the effect of an oxygen enriched environment on the red blood have observed inhibition of erythropoiesis [5, 8]. However, in some cases a hyperoxic environment may, on the contrary, stimulate erythropoiesis [1, 2, 11].

In our previous investigations [3], when albino mice were kept for short times and for periods of 10 days in an atmosphere with an increased partial pressure of oxygen, the effect was mainly to cause signs of inhibition of regeneration of the red blood.

The present investigation is an attempt to carry the study of the effect of oxygen on erythropoiesis a stage further. Experiments were carried out on animals exposed to more intensive or more prolonged hyperoxia.

To obtain a more accurate picture of the dynamics of regeneration of the red blood of the experimental animals, in addition to the usual methods of analysis in a series of experiments the method of determining the resistance of the erythrocytes to acid hemolysis was used [7]. The acid resistance of the erythrocytes reflects the relative proportions of younger and older cells. The index of resistance was used as criterion. The higher this index, the higher the mean resistance and, consequently, the higher the percentage of young erythrocytes in the blood tested.

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Experiments were performed on CC55W albino mice and Wistar albino rats aged 2-3 months. Blood was taken from the tail. About 100 animals were used in each series of experiments.

In the experiments of series I the mice were kept continuously for 15 days in an atmosphere consisting of 60% oxygen and 40% nitrogen. Blood was taken several times both during and after exposure.

As Fig. 1 shows, the erythrocyte count fell during the first days of existence in the hyperoxic medium and at the beginning of the recovery period, while on the remaining days it was slightly below the initial level. The hemoglobin concentration likewise was slightly lower, but by the end of exposure and, in particular, after a return to ordinary air, it rose appreciably.

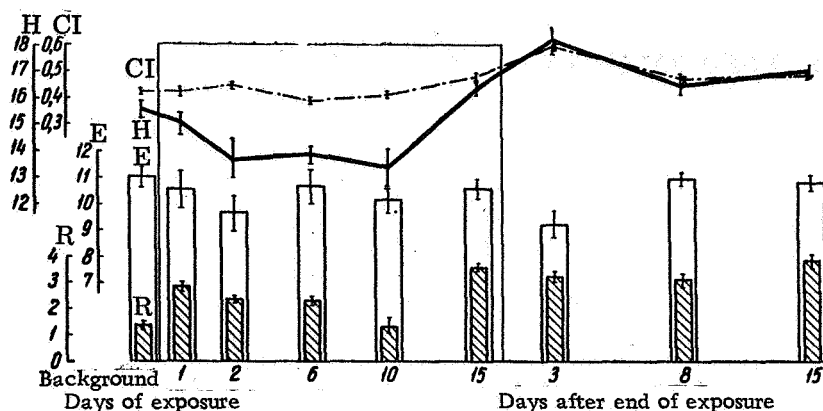


Figure 1. Effect of Exposure for 15 Days to a Medium with 60% O₂ Content on Red Blood of Mice:

CI Color Index; E — Erythrocytes, in Millions/mm³; R — Reticulocytes, %; H — Hemoglobin.

The reticulocyte count in the blood of the mice exposed to a hyperoxic atmosphere was increased (except on the 10th day), reaching a maximum on the 15th day, and the level remained high after the end of exposure.

Hence, a long exposure to a relatively moderate degree of hyperoxia had a tendency to stimulate erythropoiesis in mice. The small decrease in the erythrocyte count and hemoglobin concentration in the peripheral blood may be attributed to retention of blood in depots under the influence of oxygen excess [6].

In the next series of experiments a short exposure to intensive hyperoxia was /300 given. Albino mice inhaled oxygen at a pressure of 2.5 atm. for 90 min.

The erythrocyte count in the blood of the experimental animals (Fig. 2) after the experiment was only slightly different from before; a small decrease was found on the 6th day only. The percentage of hemoglobin showed no statistically significant deviation in either this or the next two series of experiments, and it is therefore not shown.

Soon after removal of the mice from the chamber, an increase in their reticulocyte count was observed. Since it was too soon for changes in hemopoiesis to become manifest, this increase probably indicates a redistribution of the blood cells under the influence of a hyperoxic environment [2]. Two days after the experiment the percentage of reticulocytes fell below the initial level, but then rose again; at about the 10th day this index had fallen again considerably, returning to normal by the 15th day. It is easy to see that the index of resistance of the erythrocytes shows similar periods of rise and fall, although these fluctuations do not coincide completely in time with changes in the reticulocyte count.

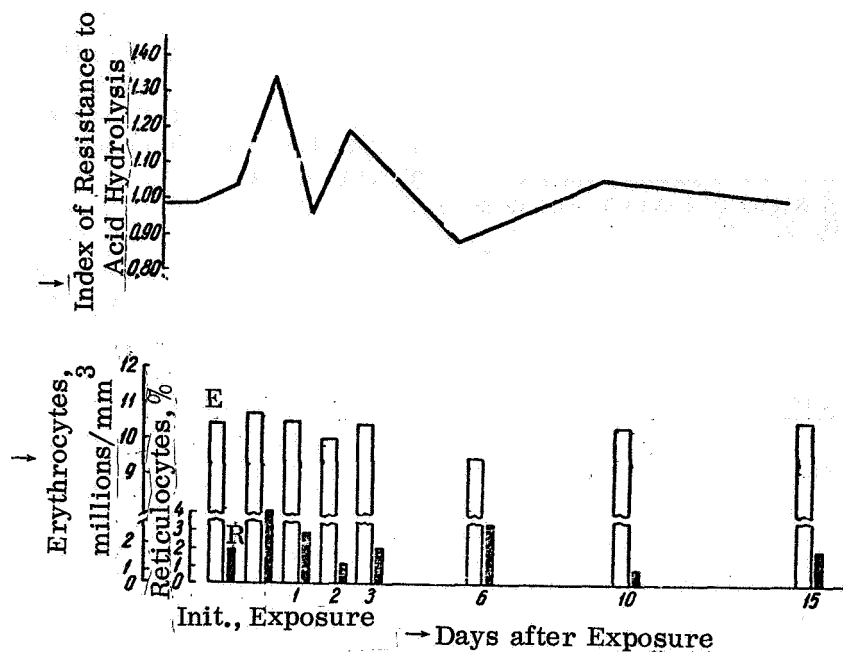


Figure 2. Effect of Exposure for 90 min to O_2 Under Pressure (2.5 abs. atm.) on Red Blood of Mice. Legend as in Fig. 1.

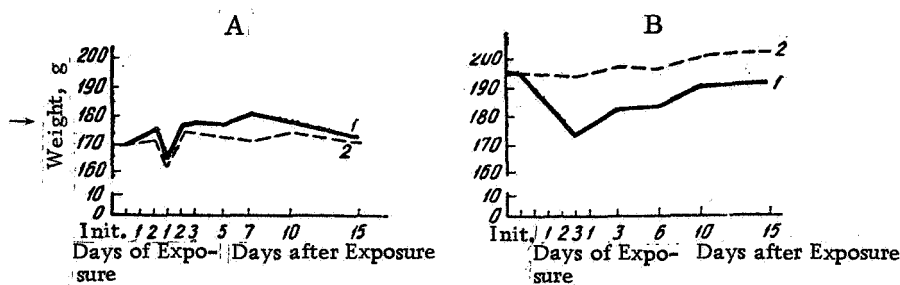


Figure 3. Effect of Exposure to O_2 for 40 h (A) and 72 h (B) on Weight of Rats. 1) Experimental Group; 2) Control.

Exposure to compressed oxygen thus caused a periodic alternation of a rise and fall in the number of young erythrocytes entering the bloodstream. /301

In the experiments of series III rats were placed for 40 h in an atmosphere containing 97% O_2 at normal atmospheric pressure.

Exposure of this duration did not necessarily cause the animals to develop toxic effects from the action of oxygen. Admittedly, the body weight of the rats was lowered for a short time after exposure (Fig. 3, A), but this was due to the stressor action of the experimental situation: similar changes in weight occurred in the rats of a control group exposed to an atmosphere of air in the chamber. The absence of signs of oxygen poisoning is also demonstrated by the curve of respiration rate (Fig. 4, A): in an atmosphere of oxygen the animals' breathing became slower, in agreement with data in the literature [6, 10, 13], returning to the normal rhythm when they were replaced in an atmosphere of air.

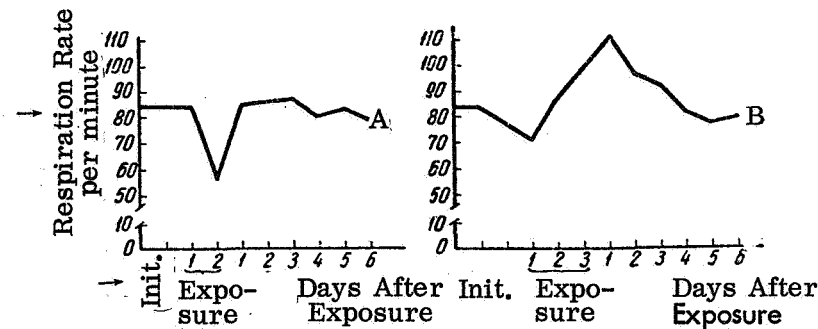


Figure 4. Effect of Exposure to O_2 for 40 h (A) and 72 h (B) on Respiration Rate of Rats.

After the end of the exposure, the number of erythrocytes circulating in the blood of the experimental rats increased (Fig. 5), on account of the redistribution of the blood already mentioned. Later the erythrocyte count fell (reaching a minimum on the 5th day), but by the 15th day it was a little above normal. /302

The reticulocyte count showed a considerable decrease on the 2nd day after the end of exposure, exceeded the initial level on the 10th, and was back to normal on the 15th day. After a short period of decrease, the acid resistance of the erythrocytes rose and remained high throughout the period of observation.

To judge from the index of resistance of the erythrocytes, marked rejuvenation of the red cell composition of the blood was observed. However, this conclusion is contradicted to some extent by the low percentage of reticulocytes which persisted for 5-7 days after the experiment. It may be that in this case the peripheral blood was enriched, not with young erythrocytes in general, but with young cells which had achieved a certain degree of maturity and had lost their reticular substance.

In the experiments of series IV the rats were exposed to 97% oxygen for 72 h. According to data in the literature [12], after such an exposure the animals must develop oxygen poisoning and lung lesions. In fact, the experimental rats lost weight for some time (Fig. 3, B) and their respiration rate was considerably increased toward the end of exposure, especially after the animals returned to an

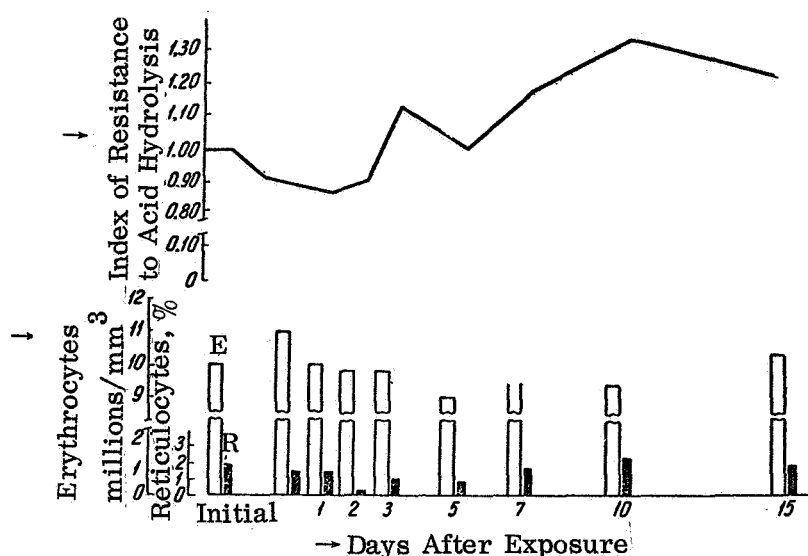


Figure 5. Effect of Exposure for 40 h to O₂ on Red Blood of Rats. Legend as in Fig. 1.

atmosphere of air (Fig. 4, B). In most of the animals autopsied after exposure to oxygen lung lesions were found: hepatization, edema, and pleural effusion. /303

It is clear from Fig. 6 that soon after exposure to an atmosphere of oxygen the number of erythrocytes in the peripheral blood rose and then fell. These changes were more abrupt than in the experiments of series III, although they took place in the same direction.

By the 3rd day after the end of exposure the reticulocyte count had fallen by half, but it then rose again and on the 10th day it had almost regained its initial level. The index of exposure fell considerably soon after exposure, but on the 3rd-6th day it was above its initial value.

As a result of the toxic action of oxygen, stimulation of erythropoiesis evidently took place after a short period of inhibition. The fact that the number of erythrocytes in the blood nevertheless remained low may be interpreted as the result of increased hemolysis.

The results described indicate that a hyperoxic environment has a complex effect on the red blood. This is presumably the reason for the conflicting nature of the results described by different workers studying this problem.

Extensive experiments have shown, for instance, that an increase in the partial pressure of oxygen in the environment may produce an effect on the hemo- /304

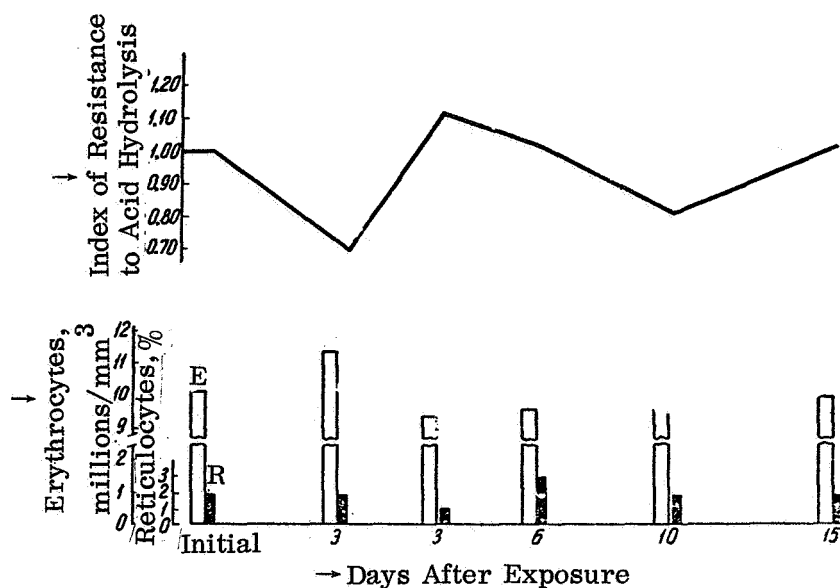


Figure 6. Effect of Exposure for 72 h to O_2 on Red Blood of Rats. Legend as in Fig. 1.

globin concentration, and the erythrocyte and reticulocyte counts in the blood of animals which differs from one case to the next [14].

In our experiments the dynamics of the age composition of the red blood was composed of alternating periods of rise and fall of the percentage of young forms of erythrocytes.

It may be postulated that an excessive oxygen concentration in the blood reduces the natural stimulus to erythropoiesis, i. e., acts in the opposite direction to the effect of oxygen lack. However, this action is complicated by a number of factors. First, sudden exposure to hyperoxia, by causing spasm of the peripheral vessels, retention of blood in storage depots, and other compensatory reactions restricting the supply of oxygen [6], may lead to tissue anoxia, which is especially severe if lung lesions develop. In such cases the hypoxic state of the animal is most acute at the moment of change from an atmosphere with a raised partial pressure of oxygen to a normal atmosphere. The result of this "hyperoxic hypoxia" [4, 9] must naturally be stimulation (and not inhibition) of erythropoiesis.

It is clear from what has been said that the effect of oxygen on the blood system cannot be expected to be consistently in the same direction. Depending on the degree of elevation of the partial pressure of oxygen in the atmosphere and the time spent by the animal in such an atmosphere, as well as on its adaptation to hyperoxic conditions [14], the net result will be either inhibition or stimulation of erythropoiesis.

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POSSIBILITY OF REDUCING THE TOXIC ACTION OF CARBON DIOXIDE ON THE LIVING ORGANISM

V. P. Zagryadskiy, I. Yu. Sidorov and E. K. Sulimo-Samuylo

Despite numerous investigations of the effect of changes in the percentage content of CO_2 on the animal organism, very little study has so far been given to the prolonged action of small concentrations of CO_2 on the body. Data in the literature [6, 10, 11] show that even a small rise in the CO_2 percentage in the inspired air may have an unfavorable influence on the state of the organism, reducing the ability to work and the resistance to various factors (physical exertion, respiration under increased pressure, overloading, etc.). /305

The range of compensation which is possible by the body relative to the gaseous components of atmospheric air (CO_2 , O_2) is very limited. Sensitivity of the body is particularly high to CO_2 , oxygen taking second place. So far as nitrogen is concerned, although it is present in the atmosphere in high concentration its complete replacement by helium evidently has no appreciable effect on the body [2].

The smaller the percentage of a biologically active gas in the inspired air, the more sensitive the body therefore is to an increase in its percentage. In fact, in order to produce hyper- or hypoventilation, it is only necessary to change the concentration of CO_2 in the alveolar air by $\pm 0.5\%$. Meanwhile, an increase or decrease of several percent in the oxygen concentration has no appreciable effect on changes in respiration. Consequently, the body is much more sensitive to changes in the concentration of carbon dioxide than of oxygen.

At the same time, however, the body is many times more resistant to an increase in the CO_2 concentration in the inspired air than in the oxygen concentration. If, for example, the partial pressure of CO_2 in the inspired air is increased by 20 times compared with that in the ordinary atmosphere (from 0.23 to 4.56 mm Hg), only a change in respiration is produced, whereas an analogous increase in the partial pressure would cause death of the organism from hyperoxemia (an increase of pO_2 from 159.5 to 3192 mm Hg, i. e., to 4.2 atm. pure oxygen).

Any change in the gaseous composition of the surrounding atmosphere, accompanied by a change in the composition of the alveolar air, may disturb the constancy of composition of the internal milieu of the organism. The inevitable consequence of this is the occurrence of compensatory reactions by various systems of the body, and especially of increased respiratory function and cardiovascular activity. /306

If compensation is well developed, the organism may begin to function on a new level. However, in some cases such compensation costs the body very dearly, especially if the action of the gaseous environment of modified composition continues for a long time. If, therefore, the composition of the gaseous environment is changed for a long time, reliance cannot be placed entirely on the adaptive, defensive reactions of the body itself. It may receive important aid under these conditions from the creation of optimal proportions between the gaseous components of the atmosphere, at which the unfavorable action of an increase in one of them will be masked by the positive effect of the action of another gaseous component. Such an effect may be anticipated because of the well-known biological antagonism between CO_2 and oxygen and of the mechanisms of compensatory reactions of the body during exposure to changed concentrations of these gases.

In this connection it is pertinent to recall investigations which demonstrated the beneficial effect of addition of CO_2 to hypoxemic mixtures on the body [3,7], the potentiation of the narcotic action of high CO_2 concentrations by a decrease in the oxygen concentration in the inspired mixture to 12-15% [4], and the shortening of the recovery period after prolonged CO_2 poisoning by administration of pure oxygen [5].

These investigations show that if the organism is exposed to modified conditions of its gaseous environment, its state will depend on the ratio between the oxygen and CO_2 concentrations. They also confirm P. M. Al'bitskiy's view [1] that definite antagonism between oxygen and carbon dioxide exists in the living organism.

It may be supposed that the basis of antagonism between oxygen and CO_2 is the difference between the action of these gases on the state of the metabolic processes, which are inhibited by carbon dioxide and stimulated by oxygen within a definite range of their concentrations.

For the sake of these considerations we decided to conduct an investigation in order to find ways of preventing the toxic action of CO_2 on the body.

In our investigations during previous years we found that if animals are kept for 5-6 h or for many days in a gaseous environment with 3-5% CO_2 , this is followed by a long period of inhibition of activity of the central nervous system. If, on the other hand, the gas mixture is enriched with oxygen (to 35-40%), the period of this aftereffect is reduced by half.

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This suggested that oxygen could be used to limit the unfavorable effects of carbon dioxide on the animal organism.

The most marked unfavorable effect of prolonged exposure to CO_2 was expressed as lowering of the animal's resistance to overloads, to breathing under

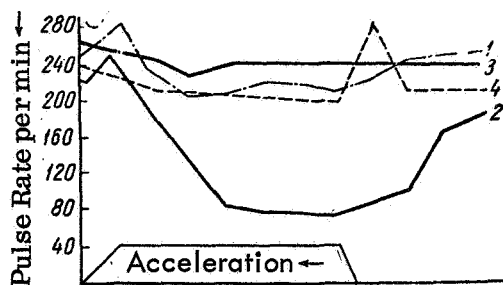


Figure 1. Changes in Heart Rate of Rabbits During the Action of Radial Accelerations Before and After a Stay in a Gaseous Environment with an Increased CO_2 Concentration and with Different Oxygen Concentrations.

1 and 3) in Initial State; 2) After a Stay in 5% CO_2 for 5 h; 4) After a Stay in 5% CO_2 and 34% O_2 for 5 h.

increased pressure, and to physical exertion. If the animals were kept for 5 h in 5% CO_2 and a normal oxygen concentration, for instance, in some cases disturbances of cardiac activity developed (disturbances of conduction and excitation of the myocardium, myocardial infarction) during overloads, together with paresis of the hind limbs, prolonged desynchronization of the α -rhythm on the EEG, and so on.

After an increase in the concentration of oxygen in the gaseous mixture to 35%, the ability of the animals to tolerate overloads, as shown by the changes in respiration, pulse, ECG and EEG, was affected relatively little by comparison with what took place before the animals' stay in the gaseous environment. Curves of the changes in the pulse of rabbits subjected to the action of radial accelerations of identical magnitude before and after a stay in a gaseous environment with an increased CO_2 concentration and with different concentrations of oxygen may serve as an example (Fig. 1). They show clearly that both the

degree of inhibition of cardiac activity and the time taken for it to recover were much reduced if an increased concentration of oxygen was present.

In an autopsy on animals subjected to the action of accelerations after a stay in a gaseous environment with an increased CO_2 concentration extensive hemorrhages located mainly along the course of the ribs were very often found. If the gas mixture contained an increased percentage of oxygen, the hemorrhages in the lungs were small and petechial. Many emphysematous areas were found. Histological analysis (V. B. Barsukovskiy) after exposure to CO_2 and overloading revealed multiple hemorrhages (partial and massive) in the interstitial tissue and also hemorrhages inside the alveoli.

In rabbits subjected to overloads after a stay in a gaseous environment with 5% CO_2 and enriched with oxygen, tiny, scattered interstitial hemorrhages were found. Sometimes collections of erythrocytes were observed in the walls of the alveoli (incrustation). The impression was created that CO_2 makes the vessels more permeable and that an increase in the oxygen concentration in the gaseous medium to some degree prevents the development of these undesirable phenomena. Unfortunately the small number of histomorphological examinations carried out does not allow more definite conclusions to be drawn.

Convincing data concerning the beneficial action of oxygen in relation to the changes caused by CO₂ were obtained in experiments in which high CO₂ concentrations were used. The object of these investigations was to study the character of the course of the "inverse" action of carbon dioxide depending on the partial pressure of oxygen. The pattern of development of the "inverse" action of CO₂ was different in cases when mice were preliminarily kept in a gaseous environment with 40% CO₂ and with a partial pressure of oxygen equal to 160 or 350 mm Hg.

TABLE: Inverse Action of CO₂ in Relation to Partial Pressure of Oxygen and Preceding Administration of Vitamins to Animals

Series	Experimental conditions	Character of inverse action of CO ₂		
		full recovery	incomp. recovery	death
I	Mice taken from gaseous environment with 40% CO ₂ and pO ₂ = 160 mm Hg . . .	51	26	23
II	Mice taken from gaseous environment with 40% CO ₂ and pO ₂ = 305 mm Hg . . .	15	71	14
III	Mice taken from gaseous environment with 40% CO ₂ and placed in one with pO ₂ = 380 mm Hg, ...	39	54	7
IV	Mice (vitaminized) taken from gaseous environment with 40% CO ₂ and pO ₂ = 160 mm Hg	68	16	16
V	Mice (vitaminized) taken from gaseous environment with 40% CO ₂ and pO ₂ = 305 mm Hg	42	51	7

In the first case, after a stay in carbon dioxide the mice had an attack of well marked clonic spasms lasting the first 1.5 min. They coincided in time with a period of slowing of respiration. Often the attack terminated in spastic respiratory arrest and death of the animal. If, however, the animal did not die, its movements were inhibited for a long time.

When the partial pressure of oxygen in the gaseous mixture was increased to 305 mm Hg, the spasms appeared sooner and the individual spasms were shorter in duration and less severe. The recovery period was considerably longer in duration, but the mortality rate among the animals was greatly reduced (table).

Further analysis of the results showed that among animals receiving vitamins the best results were obtained with those treated with vitamins concerned with synthetic processes in the cells: vitamin B₁₂, folic, pantothenic and p-amino-benzoic acids (N.D. Popov). Their administration sharply reduced the mortality rate among the mice taken from an environment with a high CO₂ concentration.

A factor of considerable importance in increasing the resistance of the body to the action of carbon dioxide is nonspecific acclimatization to various agents: a lowered partial pressure of oxygen and long-acting overloads (Chang Ju-kuo). /309

Experiments showed that adaptation to hypoxia, besides increasing the resistance of the body to this factor, at the same time increases its resistance to changed conditions of the gaseous environment, containing low and high concentrations of CO₂.

Repeated daily exposure of animals to small (up to 1.5 g) overloads for a duration of 60 min for 5 days also increased their resistance to high concentrations of CO₂ in the inspired air.

These investigations thus confirmed once again the existence of highly complex interactions in the body between the biologically active gases oxygen and carbon dioxide; they showed that an increase in the concentration of one gas (oxygen) essentially modifies the manifestation of toxicity of the other. The action of both these gases is evidently directed toward the tissue enzyme systems, the level of whose activity provides optimal conditions for metabolic processes to take place.

This is a matter of great importance for function of those nervous centers on whose activity rests the smooth flow of the chain of compensatory reactions aimed at maintaining equilibrium between the organism and the modified conditions of the gaseous environment. Provision is thus made for increasing the resistance of the organism to unfavorable factors by modifying its reactivity in the required direction. /310

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HUMAN ADAPTATION TO TEMPERATURE CONDITIONS WITH THE OBJECT OF INCREASING RESISTANCE TO HEAT

P.V. Buyanov, A.V. Beregovkin, and M.A. Migulina

In the course of his work, man often has to withstand the action of high temperatures. During space flight hyperthermic conditions may be created. In addition to protective measures, it is desirable to increase the resistance of the body to high temperatures, and one of the principal ways in which this can be done is by specific training [2, 3, 6, 8].

Because of the importance of the pattern of the astronaut's reactivity to high temperatures, A.A. Dorodnitsyna and co-workers studied methods of increasing resistance to heat by specific training. In the experiments described below, by means of clinical and physiological methods we studied the after-period, and from the stability and magnitude of the results thus obtained we judged the changes taking place in function of the cardiovascular system, external respiration, renal function, the blood system, and the level of adaptation of the subjects examined. The after-period was studied during exposures of 1 h in a chamber at +50 and +60° and of 50 min at a temperature of +70°. Exposure to temperatures of 50 and 60° was carried out daily or on alternate days. Exposure to a temperature of +70° was carried out only on alternate days. The duration of the adaptation cycle ranged from 1 to 2 months. In the background investigation, after every 10 exposures to the high temperature, at the end of the adaptation cycle, and thereafter every 25-30 days for 2-4 months, a temperature test was performed (+80° with the longest possible exposure). The criterion for stopping the experiment was an appreciable worsening of the patient's general and subjective condition, a rise of the pulse rate above 150 beats/min, or a rise of temperature by more than 3° (A.A. Dorodnitsyna and G.V. Kaliberdin).

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The objects of the clinical and physiological investigations in the after-period of the adaptation cycle and at the end of this period were to look for the appearance of changes affecting the cardiovascular system, the peripheral blood, external respiration and renal function, to determine the stability of these changes, and to ascertain the significance of the changes found in determining the level of adaptation of the subject. Besides clinical examination by specialists, spirometry was performed, the body temperature taken, the gas exchange studied, the blood and urine analyzed, the hematocrit index obtained, and tachoscillograms from the arm and arterial oscillograms recorded. By simultaneously recording the tachoscillograms and arterial oscillograms, the fundamental hemodynamic indices could be determined and an estimate made of the work of the heart, the tone of the larger arteries, and the state of the peripheral resistance. The stroke and minute blood volumes were calculated by N.N. Savitskiy's modification of the Bremser-Ranke formula.

To begin with the background data were established. Thereafter investigations were carried out periodically one every 10-15 days in the course of the adaptation cycle. At the end of the cycle the investigations were repeated every 25-30 days until disappearance of the changes which had been found. The investigations were carried out after the temperature test (80°). In most cases the orthostatic test was used. Observations and clinical and physiological tests were carried out on 17 men aged 22-26 years. All were declared healthy and fit to take part in tests involving exposure to high temperatures.

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RESULTS

First series (table). During the adaptation cycle a gradual fall of arterial pressure was observed (minimal by 11-17 mm Hg, mean dynamic pressure by 10-18 mm, and piezometric or lateral pressure by 9-12 mm Hg). The pulse pressure was slightly increased (to 10 mm Hg). Soon after the end of adaptation the arterial pressure returned to its initial level. The heart rate and cardiac output (the stroke and minute blood volumes) were not significantly changed. The trend of the changes in the precapillary system corresponded to the dynamics of the minute circulation of the blood. The velocity of spread of the pulse wave along the elastic vessels (V_e) was unchanged, while that along the muscular vessels (V_m) fell by 7-27%. The ratio V_e/V_m fell by 12-15% by the end of the adaptation period.

TABLE: Series of Investigations Undertaken

Series of investigations	Temperature in chamb. °C	Frequency of experiments	Number of subjects	Series of investigations	Temperature in chamb. °C	Frequency of experiments	Number of subjects
I	50	on alternate days	4 men	IV	60	daily	3 men
II	50	daily	4 men	V	70	on alternate days	3 men
III	60	on alternate days	3 men				

Note: Duration of experiment 60 min in series I-IV and 50 min in series V.

Although the gas exchange was investigated under conditions close to those of basal metabolism, the oxygen consumption in the initial state was raised slightly to 267-319 ml/min. In the adaptation period the oxygen utilization of two subjects rose by 13 and 15%. Their CO_2 elimination rose correspondingly.

Their respiratory quotient was essentially unchanged. The pulmonary ventilation rose in the first period and fell by 10-12% in the second period of adaptation in all subjects. At the end of the adaptation cycle the indices of gas exchange and of pulmonary ventilation returned to their initial level within a day or two. The vital capacity of the lungs and the partial lung volumes were essentially unchanged. / 313

After adaptation for 15-20 days the hematocrit volume began to increase*. A steady increase in the erythrocyte volume was found in two subjects. In the rest the increase in hematocrit index was transitory. The mean erythrocyte volume increased by 15-61%. Starting from the 30th-40th day of adaptation the leukocyte count rose gradually without any appreciable shift in the leukocyte formula.

The first control examination after the temperature test showed increases of 16-21% in the erythrocyte count and of 0.4-1.2 g % in the hemoglobin concentration. The hematocrit index was increased by 5-48% and the mean erythrocyte volume by 4-61%. The leukocyte count was increased on the average by 11%, mainly on account of the neutrophils. After the second temperature test on one subject a shift to the left of the neutrophils as far as the appearance of metamyelocytes was observed. After the temperature test the subjects' diuresis was reduced, albuminuria appeared (up to 0.033% and higher), and hyaline casts were found in the sediment (1-2 per preparation). The changes discovered disappeared during the first day as a rule, and only occasionally were detectable until the 4th day after exposure. Changes in the urine of two subjects diminished considerably in the course of adaptation.

The observed changes resulting from adaptation were unstable and disappeared in the first 10-15 days after the adaptation cycle ended. Some subjects showed poor powers of adaptation to the action of high temperatures. One subject, for example, developed signs of automatic vasomotor instability during exposure to high temperatures and he took no further part in the tests.

Second series. After each exposure the subjects were generally tired and exhausted and complained of headache. The subjective picture was more marked than in the subjects of the first series. With the systematic exposure to high temperatures the arterial pressure fell by 5-12 mm Hg. The heart rate was reduced by 3-15 beats per minute. The observed changes disappeared 10-15 days after the end of the adaptation cycle. During the exposures to a high temperature marked variations were found in the values of the stroke volume of the circulation. By the end of adaptation the indices of cardiac output had returned to their original level. The V_m/V_e ratio was reduced by 5-19% except in one subject, in whom no perceptible change took place. By the end of adaptation the initial value of V_m/V_e had been restored. During the after-period considerable fluctuations of the stroke and minute blood volumes were observed, mainly rising to 120-162% of their initial values. / 314

*The hematologic investigations and urine analyses were performed by M. Z. Ginzburg.

The oxygen consumption fell from 305-335 ml/min by 12-23%. The CO_2 elimination was reduced by 40-53%. Consequently, the respiratory quotient fell to 0.75-0.68. The minute volume of ventilation (MVV) was reduced in three subjects by 71-74%, mainly through slowing of the respiration rate and, to a lesser extent, through a change in the respiratory volume. Tests showed that 2 months after the end of the adaptation cycle the MVV had not yet reached its original level.

No appreciable changes were observed in the blood. In one animal only the erythrocyte count was lowered by 13% and the hemoglobin concentration reduced from 14.7 to 13.2 g %.

In the temperature test performed during adaptation a lowering of the arterial pressure was observed, the mean dynamic pressure falling by 4-15 mm Hg, the stroke pressure increasing by 6-20 mm Hg, and the true pulse pressure falling by 5-9 mm Hg. The velocity of spread of the pulse wave was reduced in both elastic and muscular arteries without any appreciable change in the V_m/V_e ratio. Only the orthostatic test caused some decrease in the V_m/V_e ratio instead of its usual increase observed during this test. In two subjects this type of unfavorable reaction of the vascular tone during the orthostatic test was observed throughout the period of observation at the end of the adaptation cycle (3-4 months).

After the temperature test the gas exchange increased. The leukocyte count was raised by 7-58%. A more marked leukocytic response with a shift of the neutrophils to the left and a moderate lymphocytopenia was observed in the second period of the adaptation cycle.

As a rule albumin, hyaline casts, and a few erythrocytes appeared in the urine. Changes in the urine of one subject were more marked and persisted for 3-4 days. After 2-3 weeks the changes in the urine were considerably reduced or had disappeared. During the orthostatic test the main feature was a decrease in stroke volume, with a slight decrease in the minute volume of the circulating blood and a fall in the V_m/V_e ratio.

In this series of experiments the adaptive response to systematic exposure to high temperatures included lowering of the arterial pressure, slowing of the pulse and respiration, a decrease in the cardiac output, and reduction of the gas exchange and the minute volume of pulmonary ventilation. From the dynamics of these indices after the end of adaptation it appears that there is an increase in resistance to heat which is of relatively short duration (under 1 month). Meanwhile, the effect of specific adaptation on the vascular tone continues much longer (3-4 months). Some of the changes in the hemodynamics, gas exchange, peripheral blood and urine were due not only to the influence of temperature on the human body, but also, and more especially, to individual variations which must be taken into account during job placement.

Third series. In the period of systematic exposure to high temperatures again the most characteristic features were lowering of the arterial pressure

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and slowing of the pulse. The minute volume of circulating blood showed inconstant changes (from +30 to +38%). The V_m/V_e ratio fell in only one subject. The oxygen consumption rose in 1 (+74%) and fell in 2 subjects by 20 and 32% respectively. The respiration rate became slower. The minute volume of ventilation of the lungs diminished by 21-26%. In one subject the leukocyte count rose in the course of adaptation from 7000-7500 to 9000-9500 cells/mm³. The number of leukocytes of the neutrophilic series rose by 90% and the number of eosinophils by 3.5 times. Not until 1 month after the end of adaptation to high temperatures did the leukocyte count fall to 8200 cells/mm³.

The temperature test showed a lowering of the arterial pressure, an increase in the stroke pressure, quickening of the pulse by 11-16 beats/min, and a decrease in the V_m/V_e ratio by 5-18%. The erythrocyte count fell slightly. The hematocrit volume of the erythrocytes increased by 9-13%. The leukocyte count rose by 6-50%. During subsequent tests the leukocytic response was less marked, which is attributable to adaptation. The adaptive changes in the subject with an increased leukocytic response were of short duration, for 1 month after the end of the adaptation cycle, when this test was performed after the temperature test, a marked leukocytic response was observed, with a shift to the left as far as the appearance of metamyelocytes. Traces of albumin, recent erythrocytes, and occasionally hyaline casts appeared in the urine. In two subjects the process of adaptation had no effect on the changes observed in the urine. Adaptation was of short duration and could be discerned for the first 10-20 days.

Fourth series. The same changes were found as in the first three series. The phases in the response of the circulatory system were more clearly defined. In the initial period an increase of 28-44% in the minute volume of the circulation was observed, followed by a decrease of 21-26% in the second period. A reduction in cardiac output coincided with a decrease in gas exchange. The change in vascular tone was more marked. The ratio V_m/V_e at rest was 13-23% below / 316 the initial level, and in the orthostatic test a still further decrease was observed. In one subject considerable hypotension was found in the period of systematic exposure to high temperatures. The minimal pressure fell to 44, the mean dynamic pressure up to 65, and the lateral pressure to 85 mm Hg. Bradycardia, which was characteristic of this subject in the initial state, gave way to quickening of the pulse from 44 to 70 beats/min.

This oxygen consumption fell by 16-40% and the CO₂ elimination by 11-29%. The respiration rate fell from 15-16 to 11-13 per minute and the minute volume of ventilation of the lungs was reduced by 14-28%. The decrease in MVV took place gradually, as exposures to a high temperature continued. The vital capacity of the lungs and its constituent partial volumes were unchanged.

It is an interesting fact that in this series of the investigation the hematocrit volume of the erythrocytes was unchanged, while the leukocyte count fell by 22-37%. After the temperature test a leukocytic response was observed. The leukocyte count rose by 7-124%.

In the fifth series only laboratory tests were performed. More marked changes in the blood and urine after the temperature test were observed in the first period of the adaptation cycle. In the second period they were slight or absent.

DISCUSSION

Systematic exposures to high temperatures, used in order to increase resistance to heat, did not noticeably affect the subjects' sense of fitness. In a few cases some decrease in tolerance to high temperatures was observed. These subjects showed autonomic vasomotor and endocrine instability, a marked and persistent hyper- or hypotensive response, and long-lasting leukocytosis. The differences between the subjects revealed by these tests demonstrate the importance of the individual qualities they possess, associated with inadequacy of neuro-endocrine regulation of the circulation in some cases and with differences in hemopoiesis in others. The results obtained must be taken into consideration in cases when medical examination for employment associated with exposure of the human body to high temperatures is involved.

Too little attention has been paid in the literature to the question of adaptation to high temperatures. According to some reports, persons with certain disturbances of function and with certain diseases, such as hyper- or hypofunction of the thyroid, neurological disturbances, disorders of the endocrine glands or of metabolism, and chronic diseases, possess lowered tolerance to high temperatures [12]. Our results are interesting from the standpoint that persons who, when tested after systematic exposure to high temperatures, showed persistent disturbances of function, were declared healthy on the basis of the initial clinical and physiological examination.

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We found several consistent changes in the subjects resulting from systematic exposure to high temperatures (between 50 and 70°). A definite hypotensive response was present, with slowing of the pulse, reduction of the gas exchange, a decrease in pulmonary ventilation, and so on. These changes were more regularly found in the second period of the adaptation cycle, in all series of the investigation. In my opinion, the changes discovered are important in adaptation of the body to high temperatures and they reflect the development of adaptation processes in the course of repeated exposure to them. Many investigators who have studied acclimatization in regions with a hot climate have also found, in cases when adaptation was successful, slowing of the pulse, lowering of the arterial pressure, a decrease in the cardiac output, and a reduction in the gas exchange [11, 13, 15]. The cyclic nature of the changes in the hemodynamics and gas exchange revealed by our experiments was found quite distinctly in earlier studies of acclimatization to high temperatures. Z.I. Umidova and A.D. Slonim [11, 13] found an initial increase in the stroke and minute volumes of blood and in the gas exchange. In the second period they observed a decrease in the cardiac output and oxygen utilization.

According to our findings, adaptation to the temperature factor takes place in two stages. In the first period an increase in the activity of the circulatory system and in the gas exchange is observed. In the second stage the circulating

blood volume falls and the oxygen consumption is reduced. In some cases the decrease in gas exchange is greater than the change in the minute volume of circulating blood.

This last observation indicates that the circulation of blood is not sufficiently effective and that adaptation is unstable. A decrease in the oxygen consumption with an adequate or slightly greater decrease in the volume of the cardiac output are evidence of better adaptation to high temperatures.

The lowering of the arterial pressure and simultaneous increase in the hemodynamic stroke are signs of a decrease in vascular tone. The disturbance of vascular tone is confirmed by the decrease in the ratio between the moduli of elasticity at rest and its further decrease during the orthostatic test. These distinctive features of the changes in vascular tone during systematic exposure to high temperatures must be taken into consideration when choosing methods of increasing the resistance of astronauts to heat, for a lowering of vascular tone may significantly affect tolerance to overloads and, possibly, to weightlessness. / 318

The character of the changes in the blood and urine during exposure to the temperature factor has been inadequately studied in the literature. Most investigators have studied conditions of acclimatization in a hot climate and there are few indications of changes in the blood and urine during exposure to heat under special conditions. Many workers found no essential changes in the red blood [2, 9]. F.T. Agarkov and V.N. Belyayeva [2] found cyclic responses of the red blood in their experiments. Other workers found a decrease in the leukocyte count, mainly on account of a neutropenia [1, 4, 16]. A leukocytic response with a shift of the formula to the left was observed in animals kept in a hot chamber. In the course of adaptation the degree of the changes in the white blood cells increased [4, 5]. In dogs, a leukocytic response takes place during exposure to a relatively moderate positive temperature (from +30 to +40°) and leukopenia during exposure to higher temperatures (from +50 to +60°). It is clear from these results that our knowledge of the dynamics of the blood picture during acclimatization is incomplete. We consider that an increase in the leukocyte count is observed in the first period of systematic exposure to the action of high temperatures. Later there is a gradual decrease in the leukocyte count and a reduction in the increase in the leukocyte count taking place during the temperature test. The marked and persistent leukocytic response of the blood and the considerable changes in the urine associated with direct exposure to the temperature factor indicate lowered tolerance and unsatisfactory adaptation to it.

The decisive factor in the choice of method of adaptation is the stability of the adaptation achieved. Our findings, however, justify the conclusion that the adaptation is relatively short in duration. This conclusion is confirmed by data obtained by other investigators [10] and also by the direct results of the temperature tests carried out on our subjects (A.A. Dorodnitsyna, G.V. Kaliberdin and others). Our findings thus confirm the conclusions drawn by other workers, namely, that stability of the adaptation produced by exposure to high temperatures is inadequate. In our subjects signs of adaptation were found for the first 10-30 days, depending on the magnitude of the temperature factor and on its frequency of repetition. The duration of the development of adaptation is evidently about twice as long as duration of its persistence after the exposures to the temperature factor have ceased.

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STANDARDS FOR NOISE LEVELS IN CABINS OF SPACECRAFT DURING LONG-DURATION FLIGHTS*

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Among the many problems of space medicine, those concerned with the action of noise on the astronaut occupy a special position. The uniqueness of conditions of life on spacecraft has essentially modified the character and intensity of external acoustic stimuli which may act on the human organism and, in particular, on the auditory system. From the point of view of the physical characteristics of noise and the pathophysiology of its action, space flight can be subdivided conventionally into two stages. The first step is typified by the action of short but intensive sounds and it corresponds to the period of active movement of the rockets. Many investigations of the unfavorable effects of noises with different characteristics on persons following different occupations have now been published. Detailed studies have been made of the character and degree of the general physiological and hearing disturbances produced, maximal permissible noise levels have been laid down, and the principles and means of protection against noise have been established.

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Flights by Soviet astronauts on the ships of the Vostok and Voskhod series showed that individual methods of protection against brief, intensive noises can protect a man from unpleasant acoustic sensations and enable him to continue capable of working, by creating a reliable screen from masking interference during radio communication. With the prospects of long flights in space lasting many months or even years, it is likely that the spacecraft used will be put into orbit by means of more gradual acceleration. With flights of this type the time of action of high-intensity noises will be considerably increased, and presumably their power will also be greater.

Obviously, in order to be able to forecast man's ability to work under such conditions, we must continue our investigations of the complex effects of noises of high intensity on the astronaut. Special attempts must also be made to reduce noise at its source and to choose optimal sound-insulating and sound-absorbing materials for use in the spacecraft of the future.

The second stage of a space flight is characterized by continuous and prolonged action of sounds of medium and low intensity and it corresponds to the period of orbital movement of satellites and spaceships. At this stage the main source of noise in the cabin is the assembly of life-supporting systems. Because of the conditions of flight these functions continuously, and thus create a permanent acoustic background in the cabin.

The problem of the habitability of spacecraft cabins in a long orbital flight cannot be solved without the experimental determination of permissible noise

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levels acting permanently on the astronaut. Although investigations for determining standards for high-intensity noise have been undertaken for many years and a rich experimental material has accumulated, the problems connected with the pathophysiology of exposure to sounds of medium and low intensity and with the establishment of appropriate standards have only recently begun to be studied. In a space flight lasting a few weeks or months, the factor of continuity of acoustic stimulation becomes still more important, and this necessitates the search for new ways and means of establishing permissible noise levels in the spacecraft cabin.

The control of noise parameters is known to depend on the design of the craft, the principal objects and special features of the flight, and the nature of the astronauts' activity.

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On craft without special compartments for sleep and rest, the permissible noise intensity must be close to that recommended for dwellings. According to data reported by a number of investigators, the noise level in residential buildings by day must not exceed 35-40 dB, and by night 25-30 dB. In particular, I. L. Karagodina [6] considers that the optimal noise level in dwellings by day is 35 dB at a frequency of 1000 Hz, and by night 30 dB. Similar intensities are recommended by various writers also for the conditions of space flight. According to E. B. Konecci [15], the permissible levels of continuous noise acting for long periods on man in flight must not exceed 40 dB. Slager [17], in a survey on space medicine published in 1963, also states that in the period of orbital flight the noise level inside the cabin should not, if possible, exceed 40 dB.

Unfortunately, the results of investigations of permissible noise levels in residential buildings cannot be applied directly to spacecraft cabins, for no allowance is made in these standards for the effects of factors of relative isolation, hypokinesia, etc., on the astronaut. The data given by E. B. Konecci and by Slager are not based on experimental studies of human subjects staying for long periods in a small cabin.

To establish a physiological and hygienic basis for permissible levels of noise acting throughout the 24 hours on the astronaut and continuously throughout the flight, special investigations were undertaken. In 92 experiments in which 63 subjects took part, the effects of high-frequency (up to 3000 Hz) noise with integral levels of 60-65 dB and 74-76 dB and length of exposure from 8 h to 60 days on the human auditory system were studied. Not only the acoustic environment of the cabin, but also several other flight factors— isolation, hypokinesia, the conditions of work, rest, food and clothing, etc., were simulated.

The spectral and amplitude characteristics of the noise were determined by three methods:

- measurement of the total level by means of DOU noise meters;
- recording the amplitude and frequency components of the noise with a Brüel and Kiaer microphone, with simultaneous automatic analysis on a spectrograph made by the same firm;

- recording noise through the microphone and calibrated circuit on ferromagnetic tape followed by its analysis on a "Brüel and Kjaer" spectrograph, making allowance for the total level obtained on a noise meter.

The state of function of the auditory system was determined from changes in:

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- hearing thresholds at frequencies of 125, 250, 500, 1000, 2000, 3000, 4000, 6000, 8000 and 10,000 Hz by air conduction;
- differential thresholds from a pitch of 1000 Hz;
- thresholds of masking a tone of 1000 Hz by white noise with an intensity of 70 dB;
- the time taken for recovery of the original auditory sensitivity after a standard 3-minute application of white noise with an intensity of 95 dB.

All the techniques were modified to suit the conditions of a stay of several days in a hermetically closed cabin of small size. In particular, to prevent the formation of a reflex to time by the subjects, a special device was designed which standardized the duration of the burst of sound (1 sec) and varied the interval between successive tones at random. Before the experiment the output potentials of the audometer were calibrated on the screen of an oscillograph so that the stability of the readings could be verified on any day of a long-term experiment.

The results of investigation of the hearing thresholds were analyzed by statistical methods, both by calculating the criterion of significance and by the method of least squares [3]. The subjects were questioned to discover complaints of headache, tinnitus, insomnia or loss of appetite, which they associated with the action of noise.

According to the findings of A. A. Arkad'yevskiy [1] and E. L. Orlovskaya [9], exposure for 7 h to high-frequency noise with a total level of 75 dB had no general unfavorable effect on the human body. We therefore considered that the first series of experiments could be started by studying the action of these noise levels on man, making allowance also for the added effects of a long stay in a hermetically closed and small cabin on the subjects.

After a continuous exposure of 8 h to noise with a total intensity of 74-76 dB, the hearing thresholds of the subjects were increased at the end of the experiment by 4-5 dB at low frequencies and by 5-10 dB at high. The time taken for recovery of the original auditory sensitivity, as given by the differential thresholds for pitch and the duration of retrograde adaptation, was from 1 to 2 h. The results demonstrate moderate exhaustion of auditory function.

In experiments in which the subjects were exposed to the continuous action of these noises for 24 h, a decrease of auditory sensitivity by 10-15 dB at low frequencies and by 10-20 dB at high was observed in this period. The differential thresholds for pitch rose from 0.008-0.010 to 0.012-0.022. The original auditory sensitivity was restored from 1 to 2 h after exposure had ended. Characteristically the basic indices of physiological functions (respiration rate, blood pressure, elements of the ECG) were essentially unchanged. Meanwhile,

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under these conditions the subjects complained for the first time of the irritant effect of the noise during the period of sleep and rest.

The continuous action of noise for 72 h caused the hearing thresholds to increase by 15-20 dB. The differential thresholds for pitch rose from 0.008-0.011 to 0.013-0.018. Auditory sensitivity recovered in the course of 2-3 h. The pulse and respiration rates, and blood pressure were only slightly different from initially at the end of exposure. The subjects complained of tinnitus and headache.

In experiments lasting 10 days the hearing thresholds varied at different times by as much as 10.0-17.5 dB. At the end of exposure to noise the hearing thresholds were raised by 20-25 dB. The time of retrograde adaptation was increased from 35-40 sec to 240-300 sec. Recovery of the original auditory sensitivity took 8-18 h.

During this period the subjects were troubled by headache and by noises and ringing in the ears. The response of the cardiovascular system to standard physical exertion was a slight lowering of vascular tone. During the physiological examination the subjects showed signs of fatigue. Comparison of the results of audiometry with the subjects' complaints and the results of the clinical and physiological examinations indicates that continuous (for 10 days) noise with an intensity of 74-76 dB causes marked general effects on the human body.

When the subjects were exposed to the continuous action of high-frequency noise with an intensity of 75 dB, fluctuations in the levels of hearing thresholds took place, with a diminution of fluctuation in the periods from the 5th to the 7th and from the 24th to the 27th days of the experiment. At the end of the experiments the hearing thresholds were raised by 25-30 dB. The time of retrograde adaptation was increased by 3-5 times. Recovery of the initial auditory sensitivity took place in 48-50 h. A characteristic feature distinguishing these investigations was the constant complaints throughout the experiment of the irritant and fatiguing action of the noise. After prolonged exposure to the stimulus, the subjects heard a noise in their ears continuously for 24 h. The investigations showed that by the end of the experiment there was a decrease in the amplitude and frequency of the α -rhythm on the EEG, with superposition of diffuse slow waves. Control experiments with relative isolation and hypokinesia showed that continuous exposure to noise for 30 days has a definite unfavorable action on the central nervous system and the auditory system.

These investigations demonstrated that the continuous and periodic action of high-frequency noise with an intensity of 75 dB on the human subject causes effects which differ both in their character and in the degree of modification of the function of the auditory system. In case of the periodic action of noise (up to 7 h per diem) a cumulative effect is observed only after many months and years; continuous exposure, on the other hand, gives rise to these effects after only 10 days.

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The experimental results obtained showed the need for further research to establish rational levels of the constant acoustic background in the spacecraft cabin during long flights.

For this purpose, in the second series of experiments the action of high-frequency noise with a total level of 60-65 dB was studied when exposure was continuous for 60 days. These experiments showed that under such conditions no significant changes take place in the function of the auditory system. The greatest increase in the hearing thresholds was observed in the first few days of an experiment lasting up to 60 days. Later, against the background of a certain scatter of the thresholds of auditory sensitivity, a tendency was observed for them to fall relatively. In the analysis of the results using the method of least squares (the relationship $y = ax + b$), the general tendency of the changes in hearing was rendered approximately by a straight line subsequently approaching the abscissa. The possibility that such reactions of the auditory system could take place with a change of acoustic environment, then becoming constant, was indicated in 1949 by G.V. Gershuni [4]. The dynamics of auditory sensitivity in experiments with noise levels of 60-65 dB were indistinguishable from the fluctuations in the hearing thresholds in background experiments when the intensity did not exceed 35-40 dB. The masking thresholds, the differential thresholds for pitch, and the adaptation time likewise did not exceed the ordinary physiological changes. As a rule the subjects did not complain of the general unfavorable effects of noise with an intensity of 60-65 dB in the periods of sleep and rest. The indices of the principal physiological functions were unchanged under these conditions [5, 8].

Persons not subjected to any special scrutiny often do not tolerate exposure to noise of medium intensity in the periods of sleep and rest perfectly satisfactorily [2, 6, 10, 14]. For this reason we attributed the results obtained to the high nervous and mental stamina of the subjects participating in these experiments.

On the basis of these investigations we were able to recommend that the constant acoustic background for the spacecraft cabin should not exceed 60-65 dB for an exposure of up to 60 days [7]. Naturally, no final recommendations regarding noise levels can yet be made, for the principal factor of space flight, weightlessness, could not be simulated in these experiments for a number of reasons. However, on careful analysis, no significant differences were found in the ability of the astronauts to tolerate noise in terrestrial experiments and during a space flight lasting up to 5 days.

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In spacecraft equipped with special compartments for working, sleeping and resting, differential noise levels must be stipulated for each compartment. The maximal noise intensity and spectrum in the sleeping and resting compartments must not exceed our established permissible levels (60-65 dB). In the ship's control compartment, where the astronaut must observe the working of the navigational instruments for a few hours, communicate verbally with the members of crew, etc., the noise levels likewise should not differ significantly from the parameters given above. When establishing noise levels in the working cabins, allowance must be made for the character of the activity and the length of time spent there by the astronauts. In the course of a watch lasting up to 4 h, the astronaut can evidently be exposed to a total noise level not exceeding 85 dB. In the auxiliary compartments which the astronaut visits periodically for short times only, higher noise levels can be allowed.

Where the intensity of acoustic stimulation exceeds 100 dB, and with allowance for its amplitude and spectral composition, the use of individual measures of protection against noise must be recommended.

By establishing correct noise standards for the different compartments of the spacecraft, the astronaut's working capacity will be maintainable at an adequate level during flights of long duration.

Because of the special conditions of space flight, it is not enough to consider only the usual basis for establishing physiological and hygienic standards, but in addition completely new problems and methods of ensuring acoustic comfort in the cabin must be examined. Among the other stimuli informing the astronaut about the course of the flight and the state of the external environment during space flight, acoustic stimuli stand out as the most important. Hence, aside from the general physiological and hygienic aspect of the noise background, the psychoacoustic effects of noise assume special significance.

As was mentioned above, the main acoustic noise in the cabin during the flight as a whole is created by the continuously working assemblies of life-supporting systems. Their noise is characterized by considerable stability both of amplitude and of spectral composition. From the psychoacoustic standpoint, this noise has the character of a monotonous, unpleasant stimulus.

The pronounced cyclic nature and monotony of the stimuli under long space-flight conditions favor the predominance of inhibition processes in the central nervous system. It would therefore be undesirable to have too low noise levels in the cabin, levels described in psychoacoustics as "silence." It is necessary to stipulate not only the maximal permissible, but also the minimal level of the constant acoustic background in the cabin, when laying down standards for noise during space flights of long duration. Another extremely important task in this connection is therefore to exclude the unfavorable physiological and psychoacoustic effects of monotonous noise stimuli of moderate and low intensity. This problem has several different aspects, some of which have not yet been fully elucidated by research. In our opinion, one of the main problems is that of discovering the relationship between the amplitude and frequency characteristics of noise as a physical parameter and loudness as the expression of the psychoacoustic effect. / 326

Subjective perception of the loudness of sounds by the organ of hearing is dependent not only on the level of acoustic pressure, but also on its spectral composition, as the investigations of Fletcher and Manson, and later, of Robinson and Dadson, and other workers have shown. It can be concluded from the results of their work that the loudness of pure tones is a direct function of their intensity, and in addition, in the range of low and moderate values of acoustic pressure, it depends on the frequency of the stimulus. Perception of the loudness of sounds with a complex spectrum (as is the case with most real noises) differs from the perception of pure tones. Various artificial methods have been used to measure the loudness of noise with a complex spectrum [11-13, 16-20]. These methods are aimed at determining the subjective psychoacoustic effect of a complex noise and then working out the principles of standardization. The method envisages determination of the loudness of the noise in different frequency bands, and sum-

inating the values obtained making allowance for differences in perception of different frequency components by the organ of hearing and also for the masking effect which is invariably present in a complex spectrum. The level of loudness is determined for each band from special tables or graphs allowing for the course of curves of different loudness and the width of the filter.

We consider that by using these methods we can modify the amplitude and frequency characteristics of a constant noise background in such a way that, although the loudness is kept constant, the monotony of the noise can be avoided.

With these considerations in mind, it has been shown experimentally that a noise with loudness of 50-60 phons may be regarded as permissible for spacecraft cabins.

The system of measures aimed at regulating not merely the maximal permissible, but also the minimal noise levels, together with the development of methods of preventing unfavorable psychoacoustic effects arising from long exposure to continuous acoustic stimulation, must be regarded as a single problem: that of creating the optimal acoustic background in the spacecraft cabin during space flights of long duration.

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AUDITORY FUNCTION IN MAN AFTER A PERIOD OF SEVERAL DAYS IN AN ARTIFICIAL ATMOSPHERE

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The study of human auditory function under the conditions of a modified gaseous environment is of considerable importance for assessment of the pilot's working capacity in air and space flight.

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Investigations by Soviet and other workers have shown that the auditory system is highly resistant to the action of acute hypoxia and of an increased CO₂ concentration [3, 8, 9, 10].

After inhalation of a mixture containing 8-10% O₂ for a short time, the acuity of hearing is only slightly altered, with a tendency to diminish [9]. After inhalation of mixtures with a low oxygen concentration (under 12%) for several minutes, no deterioration of hearing was observed. In some experiments an increase in the threshold of sensitivity was actually observed at high frequencies. For the practical activity of pilots and astronauts it is important to note that loss of hearing in acute hypoxia arises only as a result of the development of syncope. It may be postulated on the basis of the results described that in acute hypoxic states the leading role in the mechanism of possible hearing disturbances is played by central (including cortical) divisions of the auditory analyzer, which are most sensitive to loss of oxygen.

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Because of the steady increase in duration of space flights, the need has arisen for the study of adaptation in man during continuous exposure for many days to a number of factors, including the artificial atmosphere of the cabin. Various authors have expressed the view that changes in the gaseous composition of the cabin atmosphere during prolonged space flights have certain advantages [6, 7].

Despite its practical significance, the effect of factors of the artificial atmosphere of the spacecraft cabin on human auditory function has received very little study, so that special investigations in this field are necessary.

The investigations of auditory function took place in three series, on subjects exposed to an artificial atmosphere for periods of 25-30 days. In all series of experiments the hearing thresholds by air conduction were determined at frequencies of 125, 250, 500, 1000, 3000, 4000, 6000 and 8000 Hz, and the readaptation time at a frequency of 1000 Hz was determined after exposure for 3 min to white noise with an intensity of 90 dB.

All the techniques used were modified to suit subjects confined for many days in a small hermetically closed cabin. The results of investigation of the hearing thresholds were analyzed by statistical methods.

In Series I, when the subjects were kept for many days at a lowered barometric pressure (380 mm Hg) but with a normal oxygen pressure (150-160 mm Hg), the dynamics of auditory sensitivity showed some degree of inconstancy. The highest hearing thresholds were found in the first half of the experiment. Later, against the background of a constant scatter of thresholds of auditory sensitivity, all the subjects showed a uniform tendency toward a relative increase. In the analysis of the results by the method of least squares (the relationship $y = ax + b$), the general tendency of the changes in hearing when plotted graphically approximated to a straight line gradually approaching the abscissa. The time of readaptation varied on different days of the experiment from 48-70 to 110-150 sec. This test is highly labile and no definite trend can be discerned. The hearing thresholds in quietness after the end of a long exposure were essentially indistinguishable from the initial values. Consequently, a stay of many days under conditions of a lowered barometric pressure (308 mm Hg) but with a normal partial pressure of oxygen (150-160 mm Hg) has no significant effect on the auditory function in man. /329

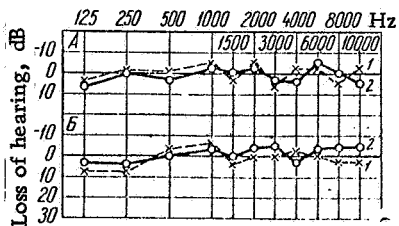


Figure. Hearing Threshold of Subject I Before a Stay in a Helium-Oxygen Environment (A) and After the end of Exposure (B). 1, 2-Right and Left Ears.

In the experiments of Series II the subjects were kept for 30 days in an atmosphere containing from 1 to 2% CO₂ [7]. No marked changes in the dynamics of the hearing thresholds and the readaptation time were observed. However, the tendency toward an increase in the hearing thresholds during the first 1-6 days of the 30-day stay was very strong. The hearing thresholds on the 1st day of the experiment, for instance, were 15-17 dB higher than those on the 21st-22nd days of exposure. Signs of fatigue of hearing were detected in these subjects after the end of the experiment. Hence, a stay of 30 days in an atmosphere with a CO₂ concentration of between 1 and 2% had no adverse effect on the human auditory analyzer.

In the experiments of Series III the auditory function was studied in subjects after a stay of 25 days in a helium-oxygen atmosphere. In this series the maximal increase in hearing thresholds was found when the subjects were transferred from the normal atmosphere to one of helium and oxygen. The variations in hearing thresholds on different days of the experiment did not exceed the normal physiological range. The readaptation time varied from 40 to 180 sec. After the end of the experiments the hearing thresholds in quietness practically coincided with the background data. It may therefore be concluded that a stay in a helium-oxygen atmosphere has no specific effect on the human auditory analyzer (figure).

The elevation of the hearing thresholds on the first days of an experiment lasting many days may be regarded as an initial adaptive response of the auditory analyzer to new and unusual influences. A sudden change from the ordinary environment to existence in an artificial atmosphere is accompanied in man by modification of many previously established and stable habits. These conditions make fresh demands on the body and, in particular, on the higher levels of the central nervous system and the analyzers, and they give rise to corresponding adaptive reactions, often of a nonspecific character. For instance, in our experiments /330

very different atmospheric factors (a lowered barometric pressure, an increased CO₂ concentration, replacement of the nitrogen of the atmosphere by helium) evoked the same type of response of the auditory analyzer. The stabilization of the thresholds of hearing observed in all series of experiments in the second and third week expresses, in my opinion, successful adaptation of the body to the new conditions.

However, we observed this type of stabilization of the auditory function only during exposure to conditions producing no essentially adverse effects. An extremely interesting phenomenon is the relative sensitization of hearing observed in the second half of these experiments lasting many days. The mechanisms of these phenomena encountered in the course of dynamic audiometry performed on subjects kept for long periods in small, hermetically sealed cabins are a matter for conjecture. It is hardly likely that the increase in excitability of the central portions of the auditory system lying at the basis of sensitization was due in our experiments to the strengthening of excitatory processes in the cerebral cortex. It has been shown in man that a prolonged stay under conditions of a lowered barometric pressure and an increased carbon dioxide concentration causes depression of the α -rhythm of the EEG, a decrease in its amplitude, and the appearance of diffuse slow waves [7]. These features are observed with the intensification of inhibition in the cerebral cortex. During cortical inhibition de-inhibition of the subcortical centers takes place. It may be postulated that the increase in auditory sensitivity in the second half of an experiment lasting many days is associated with adaptive and trophic influences on the auditory centers. However, these matters require special analysis.

Many authors [2, 4, 5, 10] consider that changes in the readaptation time are dependent primarily on the state of the cortical parts of the auditory system. The intensification of cortical inhibition in the second half of the experiments was therefore evidently responsible for prolonging the readaptation time.

The fluctuations in auditory sensitivity and the changes in adaptation of hearing discovered in these experiments demonstrate the considerable powers of adaptation of the auditory analyzer in man during a stay of many days in an artificial atmosphere.

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BIOLOGICAL ACTION OF INTENSE WIDE-BAND NOISE ON ANIMALS

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Many experimental studies of the effect of sound on man and animals have now been made [1-7]. /331

For the most part these investigations have dealt with the effect of prolonged exposure to sound of comparatively low intensity and narrow spectrum on the organ of hearing and on conditioned-reflex activity. They are undoubtedly of considerable practical importance, although they deal mainly with purely clinical and physiological aspects of the problem. Another no less important aspect of this problem, its pathomorphology, has so far been inadequately studied. The literature contains only isolated references to the considerable pathomorphological changes in the internal organs of animals (cerebral hemorrhage, changes in the nerve cells, necrobiotic changes in blood vessel walls, and so on) resulting from repeated exposure to intense sound (up to 130 dB) [5].

The object of the present investigation was to study the biological effects of wide-band noise of short duration and with an intensity of up to 155 dB on dogs. Particular attention was paid to pathomorphological changes in the respiratory system. In addition, however, the character of changes in the electrocardiograph (ECG), the electroencephalogram (EEG), and respiration rate was studied. /332
The intensity of the sound for exposures of 0.6 and 3.5 sec ranged from 105 to 155 dB. The animals were placed with their backs toward the source of the sound.

The animals were sacrificed 1.5-2 h after exposure by intravenous injection of hexobarbital, exsanguination, and other methods, and autopsied. At autopsy on the animals exposed to sound with an intensity about 126 dB, hemorrhages up to 3 mm in diameter were found in the lungs, where they were located beneath the pleura in the form of convex vesicles (Fig. 1). The hemorrhages were commonest on the costal surface of the upper lobe of the right lung.

With an increase in the intensity of the noise the pathological changes in the lungs became more severe: the number and extent of the hemorrhages and emphysematous areas increased, and the emphysema became confluent in character. Despite the increase in sound intensity, the hemorrhages never, however, exceeded 3 mm in diameter.

Microscopic examination of sections of lung tissue with hemorrhages frequently showed rupture of the capillaries and larger blood vessels (Fig. 2).

However, the appearance of hemorrhages was preceded by emphysema of the peripheral portion of the lung tissue, and after exposure to sound of intensity greater than 130-135 dB, the hemorrhages also appeared on the lateral surface, giving them a nodular appearance (Fig. 3).



Figure 1. Petechial Subpleural Hemorrhages in the Left Lung (Noise Level 140 dB).

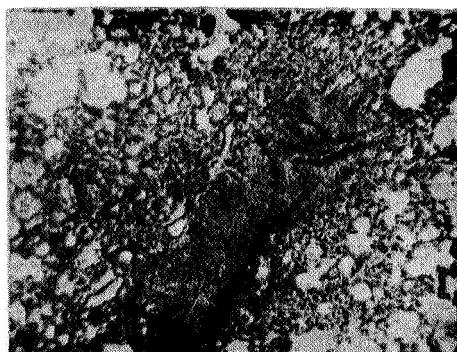


Figure 2. Focal Collection of Recently Exuded Blood in Lung Tissue. Noise Level 150 dB (Hematoxylin-Eosin).



Figure 3. Acute Emphysema of the Lung. Noise Level 135 dB.

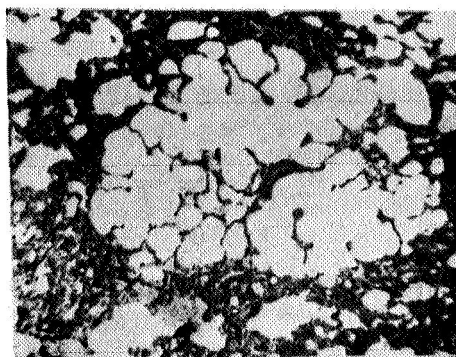


Figure 4. Microfocus of Emphysematous Lung Tissue. Noise Level 135 dB (Hematoxylineosin).

Microscopic examination of the emphysematous areas revealed focal enlargement of the alveoli, stretching of the connective-tissue structures of the alveolar walls, and compression of lung tissue (Fig. 4). /333

No pathological changes could be found in the other internal organs and in the inner ear at autopsy.

Analysis of the electrophysiological data revealed no structural disturbances in the ECG complexes or in the EEG related to the intensity or duration of acoustic stimulation. The heart rate during the first few seconds after exposure increased by 120-130 beats/min, and returned to the initial level during the next 15-40 sec.

In every case respiration became slower and irregular for 1 min immediately after exposure. The respiration rate returned to its initial level 10 min after exposure.

Observations on the higher nervous activity of the animals showed that the orienting, food-defensive, and other reflexes were fully preserved after acoustic stimulation.

To study the dynamics of regression of the pathological changes in the lungs, some animals were autopsied at different times after exposure (3, 6, 15, 30, and 60 days). As a rule, in animals sacrificed under 15 days after exposure to acoustic stimulation, signs of an acute perifocal inflammatory reaction were found.

Absorption of the exuded blood was complete during the second month of observation. No evidence of regression of the acute emphysematous changes could be seen throughout the period of observation.

Hence, this investigation showed that the threshold of pathological action of wide-band noise lies within the range 126-130 dB. As morphological criteria of the pathological action of sound, signs of acute emphysema and the presence of hemorrhages were used. /334

The localization of the pathological changes in the lungs may evidently be determined to some extent by their anatomical structure. The lungs, as a system open to the external environment, are subjected to the greatest influence of changes in pressure in this medium. Depending on the magnitude of the pressure differential created by sound in the lungs during its transformation, and on the threshold of resistance of the lung tissue to pressure changes, the severity of the lung lesions gradually increases.

However, this view of the pathogenetic effect of sound on the lungs requires further study.

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EFFECT OF SOUND ON ADRENOCORTICAL AND THYROID FUNCTION AND HIGHER NERVOUS ACTIVITY OF ALBINO RATS

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A combination of the action of physical factors of flight with nervous and emotional stress is bound to produce neuro-endocrine changes. /334

One manifestation of the adaptation syndrome is a change in function of the pituitary-adrenal system. Disturbance of its activity through exhaustion following prolonged application of stressor stimuli may lower the body's resistance to the action of unfavorable factors, notably to the factors of space flight. In many published reports data are given for changes in pituitary, adrenal and thyroid functions under the influence of various stressors. However, we know of no investigations to compare the functional state of the pituitary-adrenal system and thyroid gland during stress with the activity of the nervous system. /335

In this paper we describe the results of an experimental study of the effect of sound on adrenocortical and thyroid function and on the higher nervous activity of albino rats. An acoustic stimulus was chosen as stressor for two reasons. First, sound is readily applied in accurately measured intensity, frequency, and duration of action. Second, sound is a physical factor inevitably encountered in actual space flight.

Our experiments were carried out in the autumn and winter on Wistar albino rats weighting 150-210 g. An acoustic stimulus from a type ZG-10 audiofrequency generator, with a frequency of 650 Hz, intensity 70 dB, and duration 17 sec, was applied every 13 sec. The duration of acoustic stimulation varied from 1 hr to 14 days.

RESULTS AND DISCUSSION

Effect of Sound on Adrenocortical Function. The data in the literature relating to the effect of sound on the pituitary-adrenal system are contradictory, evidently because of differences in the technical conditions used in the experiments (different sources of sound, the frequency characteristics, intensity, and duration of action of the stimulus were not always determined, and so on). For instance, Anthony and Babcock [11], who used sound with an intensity of 110-140 dB and with frequencies of between 150-4800 Hz and between 10,000 and 20,000 Hz for 5 min, as a single exposure or daily for 4 weeks, found no changes in the cholesterol content in the adrenals or in their weight, and no changes in concentration of the plasma electrolytes. Duncan [14] observed changes in the content of corticosteroids and the ascorbic acid concentration in the adrenals after exposure to a bell for 1 min.

Changes in adrenocortical activity indicating activation of the pituitary—adrenal system under the influence of acoustic stimulus have been found by several other investigators [13, 16, 17].

In our experiments we judged adrenocortical function by the content of cholesterol and ascorbic acid in the adrenal cortex, changes in the weight of the gland, and synthesis of corticosteroids during incubation of the gland in vitro. /336
Ascorbic acid was determined by the method of Roe and Kuethner as modified by A. D. Ryzhova [8], cholesterol by the method of M. I. Prokhorova and Z. N. Tupikova [7], and synthesis of corticosteroids by adrenal slices by the method of Van der Vies [18], with certain modifications.

The results of experiments to determine the state of adrenal function are summarized in Table 1. They show that exposure to the sound used in these experiments for 1 h had no immediate effect on adrenocortical function. After exposure to the stimulus for 3 h, the ascorbic acid concentration in the glands fell. Exposure to acoustic stimulation for 6 h reduced the concentration of ascorbic acid and cholesterol. After exposure to sound for 12 h, 24 h, and 3 days, only the cholesterol concentration was reduced. Stimulation for 12 h was accompanied by hypertrophy of the adrenals also. The adrenal function of animals exposed to acoustic stimulation for 8 days was indistinguishable from normal. The absence /337
of changes in adrenal activity in response to acoustic stimulation in this case cannot be explained by exhaustion of the glands, because injection of adrenocorticotrophic hormone 3 h before the end of the 8-hour experiment lowered the ascorbic and cholesterol concentrations in the adrenals just as in intact animals.

The dynamics of changes in ascorbic acid and cholesterol concentrations in the adrenals during acoustic stimulation is shown in Fig. 1.

Production of corticosteroids during incubation of adrenal slices under these experimental conditions was unchanged. It is interesting to note that in experiments performed in the summer, but not included in this paper, an increase in synthesis of corticosteroids in vitro was observed after exposure to sound for 6 and 12 h.

Hence, like other investigators, we observed changes in adrenal functions under the influence of sound. Under the experimental conditions used, application of the acoustic stimulus for 3 h activated the adrenals, the effect reaching its maximum after 6–12 h. Absence of appreciable changes in adrenal activity after application of acoustic stimulation for 8 days may evidently be attributed to adaptation of the animal to the action of sound.

Effect of Sound on Thyroid Function. In an investigation by Yu. B. Skebel'skaya [9], the action of acoustic stimulation on thyroid function was studied (a loud electric bell was used, but no indication of the absolute intensity of the sound is given). This investigator states that a single exposure to the bell for 2 min causes changes in the histological picture of the gland capable of interpretation as stimulation of its activity. Application of this stimulus daily for 9 days caused marked inhibition of thyroid function.

During the action of combined stimuli (acoustic and photic) for 5 min every /338
hour and during a single daily exposure to acoustic, photic, and electrodermal

TABLE 1. Effect of Acoustic Stimulation on Adrenocortical Function of Albino Rats

Duration of Acoustic Stimulation	Group	Weight of Adrenals, mg/100 g Body Weight	Production of Corticosteroids by Slices, μ g/100 mg/h	Ascorbic Acid, mg% of Moist Weight	Cholesterol, Percent of Moist Weight
1 h	C	21.9 $\pm$ 1.74 (9)	7.6 $\pm$ 1.10 (5)	386 $\pm$ 18 (4)	3.7 $\pm$ 0.19 (4)
	E	22.5 $\pm$ 1.70 (10)	8.6 $\pm$ 1.29 (5)	384 $\pm$ 27 (5)	4.3 $\pm$ 0.27 (5)
3 h	C	19.0 $\pm$ 0.79 (10)	9.7 $\pm$ 0.60 (5)	440 $\pm$ 23 (5)	4.1 $\pm$ 0.13 (5)
	E	16.6 $\pm$ 0.84 (10)	9.5 $\pm$ 0.57 (5)	390 $\pm$ 16 (5)*	4.5 $\pm$ 0.38 (5)
6 h	C	14.8 $\pm$ 0.61 (9)	7.8 $\pm$ 0.44 (4)	413 $\pm$ 11 (9)	4.4 $\pm$ 0.35 (10)
	E	16.2 $\pm$ 0.66 (10)	8.9 $\pm$ 1.13 (5)	319 $\pm$ 14 (10)**	3.2 $\pm$ 0.33 (10)*
12 h	C	21.0 $\pm$ 2.39 (10)	10.3 $\pm$ 1.36 (5)	412 $\pm$ 13 (17)	3.6 $\pm$ 0.26 (18)
	E	30.5 $\pm$ 2.08 (10)**	9.6 $\pm$ 1.81 (4)	335 $\pm$ 16 (18)**	2.3 $\pm$ 0.19 (18)**
1 day	C	24.2 $\pm$ 0.97 (15)	10.1 $\pm$ 0.70 (10)	426 $\pm$ 9 (17)	3.7 $\pm$ 0.40 (10)
	E	25.0 $\pm$ 1.92 (14)	8.8 $\pm$ 1.25 (10)	383 $\pm$ 21 (17)*	2.7 $\pm$ 0.59 (10)**
3 days	C	24.2 $\pm$ 1.49 (10)	12.0 $\pm$ 0.81 (10)	495 $\pm$ 18 (10)	3.7 $\pm$ 0.17 (10)
	E	25.7 $\pm$ 1.44 (10)	10.0 $\pm$ 0.96 (10)	475 $\pm$ 21 (10)	2.9 $\pm$ 0.12 (10)**
8 days	C	26.0 $\pm$ 0.45 (20)	11.4 $\pm$ 0.47 (10)	438 $\pm$ 13 (10)	3.5 $\pm$ 0.20 (10)
	E	27.0 $\pm$ 0.73 (20)	11.9 $\pm$ 1.06 (10)	432 $\pm$ 15 (10)	3.5 $\pm$ 0.25 (10)

* $P < 0.05$, ** $P < 0.001$.

Note: Number of Experiments in Parentheses; C Denotes Control, E Denotes Experimental Animals.

stimulation for 5 min, thyroid function was found to be increased. Later it returned to its initial level, and on the following days the activity of the gland was inhibited [10].

Daily exposure for 15 days to the alternate action of a loud noise (bell, buzzer) and to a light (150-W lamp) inhibited thyroid function [4].

Two indices were used to assess thyroid function in our investigations: the level of protein-bound iodine in the blood plasma (PBI) and the histological picture of the thyroid gland (height of the follicular epithelium and character of the colloid).

The PBI level was determined by the method of Barker and co-workers [12] as modified by T. F. Komarova, D. S. Tendler, and Ye. V. Sokolova [3]. In the histological investigation the thyroid was fixed in Bouin's fluid and embedded in paraffin wax. Sections were cut to a thickness of 5-6 μ and stained by Heidenhain's

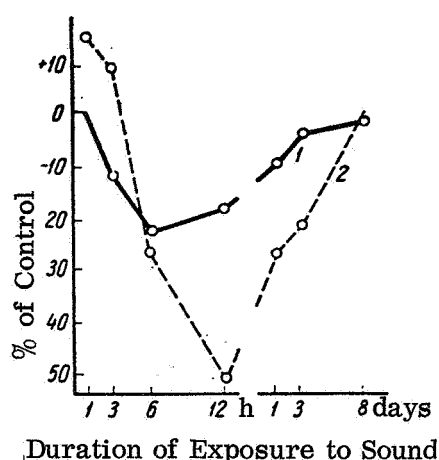


Figure 1. Dynamics of Changes in Ascorbic Acid (1) and Cholesterol (2) Concentrations in Adrenals of Rats During Action of Acoustic Stimulation.

method. To determine the mean height of the thyroid epithelial cells, the height of the cells was measured in sections passing through the center of the gland by means of an ocular micrometer with an immersion objective 90x. Altogether 500 cells were measured in each gland. The results of the measurements were analyzed by statistical methods.

For a period of 4-7 days before the series of experiments began the rats were placed in a room in which the temperature was maintained at 18-20°. Acoustic stimulation lasted for 6-12-18 h and 1, 3, 7, and 14 days. From 5 to 10 experimental and control animals were used for each period of exposure. The plasma PBI level in the rats exposed to sound for 12 and 18 h was the same as in the control animals. In the histological picture of the thyroid gland only a slight increase in height of the follicular epithelial cells with widening of the zones of colloid resorption and the appearance of interfollicular droplets were observed.

Application of the acoustic stimulus for 24 h caused a more distinct and varied effect. As may be seen in Table 2, in four of five experiments a significant increase in the PBI level was observed. In the first two experiments the height of the follicular epithelium was lowered. Demarcation into peripheral and central parts in relation to size of the follicles and of the epithelial cells lining them was sharper in these sections than under normal conditions. The follicles in the parenchyma were mainly regular and oval in shape, and were filled with a thick, sometimes stratified colloid. The follicular epithelial cells were low-cubical or flattened in shape. Their mean height was $7.97 \pm 0.048 \mu$. Very few undifferentiated interfollicular islets were present, and there were no signs of proliferation of the parenchyma. In the other three experiments no histological changes were observed in the thyroid gland.

Acoustic stimulation for 3, 7, and 14 days had no demonstrable effect on thyroid function.

The fact was noted that changes in the indices used to reflect thyroid activity give conflicting information concerning its state. Whereas the raised plasma PBI level indicates activation of the gland, the reduced height of the follicular epithelium is evidence of inhibition of its function. It will be noted that the use of different criteria for assessing thyroid function, judging by data in the literature, does not always give corresponding results [10, 15]. This is particularly true when the morphological picture of the thyroid is compared with other indices of its functional state.

However, despite the lack of uniformity in the results of our experiments, it can evidently be concluded that prolonged exposure to acoustic stimulation of a

TABLE 2. Changes in Thyroid Function Following Acoustic Stimulation for 24 h

PBI, $\mu\text{g}\%$			Height of Follicular Epithelium, μ		
Control	Experiment, and	P $\approx$	Control	Experiment, and	P $\approx$
1,61 $\pm$ 0,113	2,9 $\pm$ 0,072	0,01	9,94 $\pm$ 0,049	8,12 $\pm$ 0,099	0,01
1,79 $\pm$ 0,203	2,21 $\pm$ 0,097	0,1	12,50 $\pm$ 0,063	7,97 $\pm$ 0,048	0,01
2,50 $\pm$ 0,135	1,86 $\pm$ 0,211	0,05	10,66 $\pm$ 0,519	10,27 $\pm$ 0,10	0,6
0,97 $\pm$ 0,068	1,27 $\pm$ 0,146	0,1	13,43 $\pm$ 0,16	13,28 $\pm$ 0,146	0,5
1,86 $\pm$ 0,190	2,69 $\pm$ 0,360	0,1	10,72 $\pm$ 0,470	10,28 $\pm$ 0,071	0,7

Commas represent decimal points.

certain intensity modifies thyroid function. Exposure to sound for 6, 12, and 18 h clearly proved to be a comparatively mild stimulus, causing no distinct changes in thyroid activity. Exposure to sound for 24 h caused an increase in the plasma PBI, indicating increased thyroid function. The decrease in height of the follicular epithelium in these experiments may be attributed to increased secretion of hormone into the blood stream, evidence of which is given by the elevation of the PBI level. The absence of marked changes in thyroid function as a result of the action of the acoustic stimulus for 3, 7, and 14 days may be explained by adaptation of the animal to this stimulus.

An increase in the intensity of the stimulus could possibly give rise to a third phase—a phase of inhibition of thyroid activity.

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Effect of Sound on Higher Nervous Activity. Experiments were carried out on a separate group of rats consisting of 9 animals, using the motor electrodeless technique of A.B. Glebovskiy and V.K. Fedorov [2]. A bell was used as conditioned stimulus. The scheme of the experiment was as follows. In the first experiment the animals were first taught to turn to the right in a maze. After they had done this five times in succession without a mistake, the direction of turning was modified. The experiment ended as soon as the rats turned to the left five times in succession. The next experiment began with the rats turning to the left and ended with them turning to the right. This continued throughout the period of investigation. The state of higher nervous activity was judged from the latent period of the motor response, i.e., the time from the beginning of action of the bell until the rat left its circle, the time taken to run through the maze, and the number of mistakes made by the animal during initial learning and modification of the procedure.

The effect of sound was studied three weeks after the beginning of work with the animals, when the indices to be investigated had become constant.

To judge the changes produced by acoustic stimulation, we compared the latent periods, the times taken to run through the maze, and the number of mistakes at three time intervals: 7 experiments before the beginning of acoustic

stimulation, 7 experiments during acoustic stimulation, and 6 experiments after its end. Every day the mean values of these indices were calculated for all 9 rats. The results obtained are given in Table 3.

TABLE 3. Effect of Acoustic Stimulation on Some Indices of Conditioned-Reflex Activity of Rats

Indices Investigated	Period of Investigation			Background-Acoustic Stimulation	Acoustic Stimulation-After Stimulation
	Background	Acoustic Stimulation	After Stimulation		
Latent Period of Training.	7,7±0,85	10,6±0,51	6,4±0,49	0,02 < P < 0,05	P < 0,01
Time Taken to Run Through Maze.	7,7±1,06	10,7±0,86	8,2±0,64	0,1 > P > 0,05	0,1 > P > 0,05

Commas represent decimal points.

As the results show, under the influence of sound the latent period of reproduction of the movement was lengthened, and the time taken to run through the maze showed a tendency to increase. The temporal characteristics were modified under the influence of sound in practically all the animals, but a very slight increase in the number of mistakes during reproduction of the movement was observed in only some rats. We consider that the lengthening of the temporal indices is evidence of a state of inhibition in the animals arising under the influence of acoustic stimulation. /341

In some animals the number of mistakes was increased during the first day after discontinuing the sound, possibly indicating adaptation of the animals to this stimulus.

The very slight changes in higher nervous activity which we observed under the influence of acoustic stimulation are not in agreement with the conclusions reached by other workers [1, 5, 6], who found a decrease in magnitude of conditioned reflexes, or their actual disappearance sometimes for long periods, after acoustic stimulation of short duration. The main causes of the discrepancy, in our opinion, are: first, differences in the duration and intensity of the stimuli, and second, the fact that the authors cited used a bell as the acoustic stimulus. This stimulus, which acts specifically on the auditory analyzer of rats, causes them to develop convulsions. In Pavlova's experiments, marked changes in higher nervous activity were observed in rats giving a motor response to ringing of a bell. Monayenkov [5] also describes the variation in changes in higher nervous activity observed among animals "sensitive" and "insensitive" to the ringing of a bell. Wistar rats do not possess specific sensitivity to ringing. To a considerable extent the discrepancy between our findings and those described by the authors cited above may be attributed to different techniques used for studying higher nervous activity. All these authors used Kotlyarevskiy's motor-food method.

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EFFECT OF HYPODYNAMIA ON NITROGEN METABOLISM AND IMPORTANCE OF GRADED PHYSICAL EXERCISES FOR MAINTENANCE OF THE NITROGEN BALANCE

Yu. K. Syzrantsev

Metabolic studies in man during hypodynamia are of great importance for their practical application to space flights.

Under terrestrial conditions weightlessness can be simulated approximately by confining the subject strictly to bed or by immersing him in water. These conditions give rise to the hypodynamic and circulatory effects of weightlessness. The state of the body functions during hypodynamia has been studied in a number of investigations by Soviet and Western workers [1, 2, 5-9, 14, 18, 19].

A consideration of the physiological changes as a whole produced by hypodynamia shows that the body's functional reserves are lowered. Most workers consider that the main cause of these changes is the decrease in muscular activity, for similar changes in bodily responses can be obtained not only when the subject is strictly confined to bed, but also when he is placed in a confined space or in an armchair [3, 16, 17].

Serious attention must be given to metabolic studies in subjects under conditions of limited mobility and increased muscular activity. It is well known from clinical observations that prolonged immobilization, on account of various lesions of the bones and joints, or application of plaster casts for long periods leads to muscle atrophy.

It has been shown that during immobilization of muscles the total nitrogen content of the muscle tissue and the content of myofibrillary proteins are lowered [15]. In a nonworking muscle both quantitative and qualitative changes take place in the composition of the proteins: the content of the water-soluble protein fraction and of myosin is reduced, the muscle fibers become thinner, and the content of connective-tissue proteins increases [12]. Some increase is found in the activity of the muscle proteolytic enzymes of the limbs during their immobilization [4].

In a survey of hypodynamia, Lawton [18] reports an increase in excretion of total nitrogen by healthy persons immobilized in a plaster spica extending from mid-abdomen to the toes. In human subjects immersed in water, considerable biochemical changes were observed during the first three days of the experiment: polyuria, increased excretion of total nitrogen and of certain electrolytes in the urine, and an increase in total protein, albumin, γ -globulin and 17-hydroxycorticosteroids in the blood [14].

Physical exercises under hypodynamic conditions have been shown to increase the functional capacity of the body, to restore equilibrium of the fundamental nervous processes and autonomic functions, and to improve tissue

metabolism [9, 11]. In the course of physical training, the protein mass of the trained muscle increases, and this is accompanied by increased resynthesis of contractile proteins and increased working capacity of the muscle [13]. The study of the composition of the body after physical training shows that the proportion of the muscle component is increased or remains at the previous level depending on the extent of the physical exertion. If the changes produced by hypodynamia are examined, the question of the extent of the physical training required for prevention of atrophy naturally arises. Lawton [18] considers that the critical intensity of training is one-third of the maximal muscular force; to maintain 50-80% of the initial power, exertion of this magnitude should be given once every week.

The object of the present investigation was to study changes in the nitrogen metabolism of human subjects in hypodynamia, with or without the use of programs of physical exercises. Young, healthy subjects were used. Muscle activity was restricted by confining the subjects strictly to bed, by immersing them in water, and by isolating them in a confined space.

The diet given corresponded to the energy expenditure of the body under these conditions and was as far as possible standard in each series of experiments: the protein content was identical in the control period and during hypodynamia. The actual food consumption during hypodynamia was somewhat smaller than in the control. The range of muscle activity was controlled by the need to move when taking food, by attending to natural wants, and by carrying out the research program: recording the ECG, collecting samples of air and blood, and so on. The end products of nitrogen metabolism were studied in the 24-hour specimen of urine: the total nitrogen, urea nitrogen, nitrogen of ammonium salts, nitrogen of free amino acids, creatinine and creatine. /344

Altogether 19 experiments were performed on 19 subjects. Depending on the character of the procedures, the experiments may be divided into five groups.

In Group 1 the state of the nitrogen metabolism was investigated in hypodynamia produced by strict bed rest. A special armchair made it possible to keep the body in the horizontal position with maximal relaxation of the muscles. Hypodynamia continued for 8 days.

In Group 2 the effects of hypodynamia were investigated on subjects immersed in water in a special tank. The position of the body was horizontal. The duration of hypodynamia was 8 days.

In Group 3 the effects of hypodynamia combined with a limited program of physical exercises were studied. The subjects were kept in a confined space in semirecumbency. Twice a day they performed exercises against resistance created by rubber shock absorbers. The energy requirement of the physical exertion was 100 kcal. The experiments continued for 10 days.

In the experiments of Group 4 the effects of confinement in a somewhat larger space (a pressure chamber) for 30 days were studied. Two subjects were allowed greater freedom of movement, and twice a day they carried out a program of physical training consisting of dynamic exercises combined with static exertion. The energy requirement of training was 150-200 kcal.

In Group 5 the effects of more considerable physical exertion by subjects kept in a horizontal position for 12 days were studied. The energy requirement of the physical exertion was 400 kcal. The program of physical exercises included both dynamic and static types.

Changes in excretion of total nitrogen in the urine in the various types of hypodynamia and in hypodynamia combined with programs of physical exercises with varied energy requirements are given in Table 1.

TABLE 1. Excretion of Total Nitrogen (in g/day) Depending on Motor Activity*

Experimental Conditions	Control		Experiment		
	M ± m	No. of Investigations	M ± m	No. of Investigations	P <
Bed Rest	12,7±0,56	12	15,7±0,52	59	0,001
Immersion in Water	12,1±0,36	8	15,8±0,64	24	0,001
In Confined Space with Physical Exercises	14,5±0,69	10	17,4±0,68	29	0,001
In Pressure Chamber with Physical Exercises	13,5±0,57	8	15,4±0,38	52	0,02
Bed Rest with Considerable Physical Exertion	11,6±0,61	20	12,3±0,48	27	—

*The experiments were performed by V. N. Slesarev. The programs of physical exercises were compiled by V. V. Bozhanov and V. I. Stepanov.

Commas represent decimal points.

This table shows that the nitrogen excretion was considerably increased in these experiments except in Group 5: in this group the nitrogen excretion by the subjects remained practically unchanged.

The greatest nitrogen losses were found in the experiments of Groups 1-3. The increase in nitrogen excretion under hypodynamic conditions in the experiments of Groups 1-3 was 20-25%. Physical exercises reduced the nitrogen excretion, and the greater the energy expenditure and the more varied the physical exertion, the greater this reduction was. /345

The results obtained are in agreement with data in the literature, although increased nitrogen excretion in the urine was observed not only during the first three days of the experiments, as was the case in Graveline's experiments [14]. The changes in nitrogen metabolism were present for a longer period.

The greatest excretion of nitrogen was found on the last days of the experiment. In the tests in the pressure chamber (Group 4), increased nitrogen excretion was observed in one subject until the 18th day of the experiment.

The next step was to determine the state of the nitrogen balance in the subjects of Group 3. The dynamics of nitrogen excretion and of its balance in one of the subjects may be seen in Table 2.

TABLE 2. Nitrogen Balance (in g) of the Subject G. During Hypodynamia with Physical Exercises

Indices	Days of Experiment							
	1st	2nd	3rd	4th	5th	6th	7th	8th
Nitrogen Excretion, g .	12,7	11,6	26,9	17,4	15,4	19,1	13,6	19,6
Nitrogen Intake with Food, g	12,4	15,8	16,8	15,8	15,6	14,3	13,3	14,3
Balance	-0,3	+4,2	-10,1	-1,6	+0,2	-4,8	-0,3	-5,3
Total	-18,0							

Commas represent decimal points.

It may be concluded from analysis of this table that excretion of nitrogen takes place irregularly on different days (see 3rd, 6th, 8th days), and throughout the experiment as a whole the nitrogen balance was negative. Similar results for the state of the nitrogen balance were obtained with three subjects of Group 1. A noteworthy feature was the considerable increase in nitrogen excretion on certain days of hypodynamia (26.9 g).

Values of nitrogen excretion such as these may be observed clinically in patients with traumatic injuries (fracture of the femur, etc.). However, when interpreting this considerable increase in nitrogen catabolism during trauma, the effects of immobilization of the patient has evidently not been considered.

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Determination of the qualitative indices of protein metabolism (urea nitrogen, nitrogen of free amino acids, ammonium nitrogen, creatine and creatinine, and uric acid) revealed changes in the course of nitrogen metabolism during exposure to hypodynamia. The appearance of creatine and an increase in the excretion of creatinine were noted. The content of urea and free amino acids in the urine also increased. Neither the excretion of ammonium nitrogen nor Hasselbach's coefficient was increased, indicating that the biochemical mechanisms of ammonia fixation were undisturbed. The results of this investigation confirm data in the literature regarding changes in protein metabolism under the influence of hypodynamia: an increase in nitrogen excretion in the urine and a negative nitrogen balance, evidently on account of muscle atrophy. They also indicate a decrease in protein resynthesis in the body.

The increased nitrogen excretion corresponds to the lowered functional powers of the body under hypodynamic conditions.

It can be assumed that under the conditions of prolonged weightlessness, when proprioception of the locomotor apparatus and interoception of the internal organs are modified, the changes in protein metabolism will be still more profound and the protein loss by the body will increase. In addition, the factor of nervous and mental stress to which the astronaut is exposed in space flight cannot be ignored. We now know that during intensive nervous and mental activity, man requires a larger intake of essential protein. Probably the nitrogen excretion rises under these circumstances more than during hypodynamia. The results of the present investigation show that a program of physical exercises with an energy requirement of 400 kcal is an effective means of maintaining the body protein. /347

However, physical exercises are not the only prophylactic measure for maintaining the working ability of the body at a high level during prolonged flights. A diet with a high content of essential protein and vitamins, and especially of the vitamins concerned with amino acid metabolism (folic acid, pyridoxin, cobalamine), and other food substances is no less important. Another problem requiring analysis is the use of pharmacological agents possessing anabolic action. Among these drugs, those which merit attention are the structural analogs of the glucocorticosteroids—the androgens (for example, Nilevar, a synthetic androgen), which promote protein synthesis nonspecifically in all organs.

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EFFECT OF QUALITATIVE DIFFERENCES IN DIET ON METABOLISM IN HYPODYNAMIA

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The study of metabolism under hypodynamic conditions is of considerable importance for the assessment of dietary requirements for space flight, because the possibility of maintaining movement at the normal terrestrial level is naturally limited by the size of the spacecraft. /348

Interest in this problem for space biology and medicine is also determined by the fact that a period of hypodynamia, especially in a strictly horizontal position, is one method used to simulate the action of prolonged weightlessness on the cardiovascular system.

The results of experiments to study metabolism under hypodynamic conditions have been published in the literature [1, 3, 5, 6]. From these results it is impossible to formulate in a definite manner the main dietary requirements because metabolism was studied without paying strict attention to the food value of the daily ration. Nevertheless, the solution of these problems is of definite theoretical and practical significance.

Activity of spacecraft crew members is characterized by low energy consumption, low mobility, and high nervous and mental strain.

Since insufficient attention has been paid in the literature to the effect of qualitatively different diets in hypodynamia, it was decided to study this problem.

Seven experiments were performed on six healthy men aged 21-26 years, each experiment consisting of two stages: control (3-8 days) when there was no restriction on movement, and a period of hypodynamia lasting seven days. Hypodynamia was produced by keeping the subjects in a strictly horizontal position. The microclimate in the room was kept close to comfortable conditions for a lightly clad person at rest. To eliminate neuropsychic stress the subjects were not isolated, and this made it more convenient for studying metabolism and for strict control over the food and water consumed.

The investigations can be divided into two groups depending on the composition and food value of the diet.

The first group of observations was made on subjects receiving a diet similar to normal in its content of the principal assimilable substances and calorific value, with an adequate content of mineral substances, but slightly deficient in vitamins (except for vitamin C). Proteins of animal and plant origin were provided in this diet, and the assimilability of the diet was normal. /349

The second stage of the investigations was carried out on subjects receiving a diet closer to the basal metabolic rate in calorific value. The protein content of this diet was approximately half that of the first, but the protein was purely of animal origin, ensuring that the relative proportions of essential amino acids were as close to optimal as possible [2]. The food value of both these diets is shown in Table 1.

TABLE 1. Food Value of Diet Actually Consumed by
Subjects when Kept Under Hypodynamic Conditions
(Mean Daily Consumption)

Group	Total Protein, g	Animal Protein, g	Animal Proteins, %	Content of (in g)		Calorific value, kcal
				Fats	Carbohydrates	
First.	120,3	101,0	84	101,2	297,2	2653
Second*	70	68	98	67,1	266,0	2002

*The following supplements were added daily: vitamin A 4 mg, ascorbic acid 200 mg, rutin 100 mg, thiamine, riboflavin, and folic acid 4 mg each, pantothenic acid 20 mg, nicotinamide 30 mg, cyanocobalamine 50 µg, α -tocopherol 50 mg.

Commas represent decimal points.

Another distinguishing feature of the second diet was its increased vitamin content, resulting from the addition of vitamin preparations. Vitamins present in the active groups of oxidative enzymes (riboflavin, nicotinic acid, thiamine) were added to the diet. Addition of pyridoxin was justified by the leading role of pyridoxal enzymes in protein metabolism. Vitamins of the "synthetic" group participating in metabolism of compounds containing one carbon atom and in protein and nucleic acid synthesis (cyanocobalamine, folic and pantothenic acids) were also added. The P vitamins and ascorbic acid were added mainly because of their predominant effect on permeability of the blood vessels, while vitamin E (α -tocopherol) was included because of its positive effect on endocrine function and on muscle metabolism. The basal metabolic rate was determined during unrestricted movements before the experiment and during hypodynamia by the Douglas-Haldane method. The daily excretion of total nitrogen, and nitrogen of urea, ammonia and free amino acids was determined to provide indices of nitrogen metabolism. The daily excretion of creatinine, creatine and uric acid was also determined.

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The state of intermediate metabolism was assessed by determining the oxygen uptake of the urine and the coefficient of incomplete oxidation. Nonprotein and amino nitrogen and the content of free amino acids, sugar, cholesterol and phospholipids in the blood were determined.

The water balance was studied and excretion of the following electrolytes in the urine was determined: potassium, sodium, calcium, phosphate, chloride. Loss of chlorides by perspiration was also estimated.

The state of the vitamin metabolism was assessed from the excretion of thiamine, riboflavin, ascorbic and 4-pyridoxic acids, and N₁-methylnicotinamide, and from measurement of the resistance of the erythrocytes in hydrogen peroxide.

Certain indices of the state of digestion and changes in the intestinal microflora were also determined.

The transition from normal freedom of movement to a state of hypodynamia was accompanied by a decrease in basal metabolism by between 2 and 22%. The extent of the decrease was independent of the composition of the diet but was determined mainly by the movements preceding the experiment. The higher the intensity of movement in the period before hypodynamia, the greater the fall in basal metabolism. The pulmonary ventilation also fell to some degree but the respiratory coefficient remained unchanged.

The change from free movement to hypodynamia had no significant effect on the acid-base balance: the pH of the urine, the titrated acidity, and the excretion of phosphates were practically unchanged.

Results characterizing the state of nitrogen metabolism of the subjects under hypodynamic conditions when receiving different diets are of considerable interest. These results concerning nitrogen metabolism are given in Table 2.

In a state of hypodynamia the excretion of total nitrogen and urea nitrogen was increased despite the fact that the level of energy expenditure and basal metabolism was lower than in the preceding period. Increased excretion of the principal and products of nitrogen metabolism was observed both in the subjects receiving the first diet with an adequate protein content (120 g) and in those receiving the second diet with a low protein content (57 g).

These results suggest that the increased excretion of end products of protein metabolism is not the result of an insufficiency of protein in the diet, but is due to the state of hypodynamia. It should be emphasized that the increased calorific value of the first diet did not compensate for the increased excretion of nitrogenous components.

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It may be assumed that the increased nitrogen excretion resulted from the decrease in mass muscle tissue. This is in agreement with the fact that the creatinine excretion was not reduced. Usually when the basal metabolism is lowered, the creatinine excretion falls at the same time.

The increase in urinary amino nitrogen and the slight increase in its concentration in the blood suggests that resynthesis of tissue protein was slightly inhibited. This is confirmed to some extent by comparison of the excretion of amino nitrogen in the subjects receiving different diets. The practical absence of increase in excretion of amino acids in a state of hypodynamia in the subjects receiving the second diet was due to the more perfectly balanced amino-acid composition. This naturally facilitated tissue protein resynthesis. The positive

influence of the increased content of cyancobalamine, folic and pantothenic acids, and also pyridoxin likewise cannot be ruled out. Other vitamins probably had no significant action.

TABLE 2. Nitrogen Metabolism of Subjects in Hypodynamia and Receiving Different Diets
(Mean Values for Days of Experiment)

Indices	First Diet (3 experiments)		Second Diet (4 experiments)	
	Unrestricted Movements	Hypodynamia	Unrestricted Movements	Hypodynamia
Total Nitrogen of Urine, g/day	14,9	17,1	12,9	14,2
Urea Nitrogen of 24-hour Urine, g/day	10,9	13,1	9,29	11,5
Urea, Total Nitrogen (%)	73	77	75	81
Ammonia Nitrogen of 24-hour Urine, g/day	0,76	0,85	0,52	0,47
Ammonia Nitrogen, Tot. Nitrogen (%)	5,1	4,85	4,3	3,3
Amino Nitrogen of Urine, g/day	0,387	0,535	0,345	0,380
Creatinine, g/day	1,62	1,64	1,48	1,68
Creatine, g/day	0,07	0,06	0,09	0,136
Amino Nitrogen of Blood, mg (%)	—	—	6,02	7,4
Nonprotein Nitrogen of Blood, mg %	—	—	36,4	34,1

Commas represent decimal points.

The increased destruction of tissue proteins following the change to restricted movement can also be excluded as the main cause of the negative nitrogen balance because of the absence of increase in the blood nonprotein nitrogen concentration under hypodynamic conditions.

Despite the fairly intensive nitrogen metabolism, some qualitative indices showed a tendency to improve; the ratio between urea nitrogen and total nitrogen, for instance, rose slightly but the ammonia coefficient showed no increase, although in the subjects receiving the first diet some increase in ammonia excretion was observed. /352

Some idea of the state of oxidative processes and of intermediate metabolism was given by determination of the oxygen uptake of the urine and calculation of the coefficient of incomplete oxidation. The oxygen uptake of the urine in subjects receiving the first diet was 19.0 g O₂/day, falling to 16.0 g with the transfer to hypodynamia. The content of incompletely oxidized products excreted in the urine

of the subjects receiving the second diet was diminished: 16.9 g O₂ in subjects moving freely and 13.2 g O₂/ day in subjects in a state of hypodynamia. The coefficient of incomplete oxidation of the urine was about the same in both groups of subjects (1.28-1.27 in the subjects moving freely and 0.89-0.91 under conditions of hypodynamia).

Results of determination of the oxygen uptake of the urine indicate that the second diet may have advantages. The lower excretion of incompletely oxidized products may be explained by the better balance of the protein part of the diet and by the fact that it contained increased amounts of vitamins incorporated in tissue oxidative enzymes (riboflavin, nicotinic acid, thiamine), and improving the utilization of proteins and carbohydrates (pyridoxin, thiamine, etc.).

It is a very important fact that the excretion of nitrogenous compounds was lower in the subjects receiving the second diet, with its lower protein content and lower calorific value, corresponding to the utilization of 90 g nitrogen; in the subjects receiving the first diet and kept under hypodynamic conditions the corresponding figure was 106 g. A more economic utilization of protein in subjects receiving a more balanced diet of higher biological value was observed previously during the study of low-calorie diets [4].

A possible explanation of the lower values of excretion of total nitrogen in the urine of the subjects receiving the second diet may be a corresponding increase in nitrogen excretion with the stools, i. e., a decrease in assimilation.

Since there is no information in the literature concerning the assimilation of food by subjects under hypodynamic conditions, this possibility could be excluded only by an experimental study of the assimilation of the protein of the second diet by subjects allowed different degrees of mobility. This study showed that hypodynamic conditions have no significant effect on the rate of assimilation. In freely moving subjects, for instance, the degree of assimilation of the dietary protein varied from 86 to 92.5% while under hypodynamic conditions it varied from 85 to 90.2%.

The carbohydrate metabolism showed only very slight changes with the transfer to hypodynamia, the blood sugar level falling by 13-35% compared with normal conditions, although the carbohydrate consumption was not decreased. This change in carbohydrate metabolism is most probably attributable to a decrease in adrenalin secretion. The blood sugar remained high (not below 95 mg%). The pyruvic acid excretion fell slightly, especially in subjects receiving the second diet, evidently because of the increased thiamine content. This indicates that the course of carbohydrate metabolism was perfectly satisfactory. /353

Determination of normal values of water intake was not among the objects of this investigation, because it depends to a greater degree on the microclimate of the room, but at the same time the results obtained relative to water and mineral metabolism under hypodynamic conditions are of considerable interest. Their analysis revealed closely similar values of water intake before the experiment and under hypodynamic conditions.

Because of the strict uniformity of the diet, the volume of metabolic water formed in the body per day was 251 ml. The mean daily diuresis likewise was similar: 722 ml in the control and 745 ml during hypodynamia. However, changes were found in the kidney function. For instance, before hypodynamia on the average 89% of the water drunk was excreted after a water loading test, after hypodynamia this fell to 41% in the same period (2% of the body weight). This observation requires further study and interpretation.

No significant changes took place in mineral metabolism under hypodynamic conditions. The excretion of potassium, sodium, and chloride showed a tendency to decrease (by 13.38 and 18% respectively), while the excretion of calcium and phosphate, on the other hand, rose slightly (by 8 and 13%), possibly because of the absence of load on the locomotor system, resulting in changes in the bone tissue. Determination of the vitamin balance of the body revealed differences depending on the composition of the diet (Table 3). In subjects with restricted movements these indices of vitamin metabolism either remained unchanged (thiamine, riboflavin) or improved. Characteristically, all the indices of vitamin metabolism were better in the subjects receiving the second diet. The results were identical only in the case of ascorbic acid: its increased excretion under hypodynamic conditions depended on the diet received.

TABLE 3. Indices of Vitamin Balance of Subjects Receiving Different Diets Under Hypodynamic Conditions (Mean Data Per Day of Experiment)

Excretion in Urine Per Day	First Diet		Second Diet	
	Free movement	Hypodynamia	Free Movement	Hypodynamia
Ascorbic Acid, mg.	13,2	119,6	18,5	78,5
Thiamine, μ g	93	86	234	215
Riboflavin, μ g	77	69	498	507
N ₁ -Methylnicotinamide, mg.	3,1	6,78	7,3	9,6
4-Pyridoxic Acid, μ g	552	753	691	704

Commas represent decimal points.

Despite the additional daily consumption of 4 mg pyridoxin by the subjects receiving the second diet, satisfactorily high values of 4-pyridoxic acid excretion could not be obtained. This may be explained by the decrease in microbiological synthesis of the vitamin in the intestine because of the high rate of assimilation of dietary protein, and a decrease in the number of microorganisms in the intestine. Tests showed that the number of bacterial cells per gram of stools fell by 100 times, and since the weight of the stools also fell, this decrease was still more marked. /354

The general conclusion may be drawn from the results described that hypodynamic conditions have a considerable effect on metabolism, the intensity of which depends on the composition of the diet received. The main requirement of a diet for such conditions is that it should aim to be as biologically balanced as possible, and attempts should not be made to compensate for changes in metabolism by increasing the content of individual components of the diet. This applies most emphatically to protein metabolism. The provision of a diet with a calorific value much higher than that needed by the body likewise cannot be justified.

The diet for hypodynamic conditions must be as balanced as possible in its content of individual components and adequate to the level of energy expenditure. Deviation from this general rule concerning diets for use under conditions of restricted mobility leads to more severe changes in metabolism than when movement is unrestricted.

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NUTRITIONAL STATE OF HUMAN SUBJECTS KEPT FOR LONG PERIODS
IN A HORIZONTAL POSITION AND SUBSEQUENTLY EXPOSED
TO ACCELERATION

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One method of stimulating the action of weightlessness on the human body under terrestrial conditions which is frequently used for research purposes is by keeping subjects in a strictly horizontal position and restricting their movement as far as possible.

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Since a prolonged stay in the horizontal position and restriction of movement has significant effects on metabolism and the cardiovascular system, it is interesting to study the action of overloads at the end of a period under these conditions.

The inclusion of overloading as the final stage of the experiment is also important as a function test. By applying accelerations it is possible to determine the intensity of metabolic processes and to assess to some extent the value of the diet received.

The main purpose of the present investigation was to study the nutritional state of a human subject kept in a horizontal position and with restricted movement. Insufficient attention has been paid to this problem in the Soviet and Western literature, especially if the combined action of hypodynamia and subsequent overloading of the body is concerned.

Several workers have found that prolonged and strict bed rest leads to considerable changes in the motor apparatus, with the development of a varied degree of muscular atrophy. Limitation of muscular activity under hypodynamic conditions lowers the tolerance of the cardiovascular system to physical exertion, increases the energy cost of a unit of work and the oxygen debt, and lowers resistance to the orthostatic test [2, 6]. Changes have also been found in protein, water and salt metabolism [1]. The 24-hour diuresis was considerably increased, and the excretion of nitrogen, sodium, potassium, phosphorus and calcium in the urine was increased to a lesser degree. An increase in the total protein, albumins, γ -globulin, 17-hydroxycorticosteroids and sugar in the blood has been described [3-6].

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The changes in metabolism (protein, water, salt, carbohydrate) described above are reversible, for the biochemical indices return to normal in the period after hypodynamia.

The observations made by the authors cited above were concerned mainly with changes in metabolism in the body arising under the influence of prolonged

restriction of muscular activity, whereas we were concerned with exposure not merely to hypodynamia alone, but also to subsequent overloading of the maximal tolerable intensity. The direction of the overloads was "sternum—spine."

Investigations of some aspects of the nutritional state of subjects during hypodynamia and preceding exposure to overloading were carried out on three healthy young persons of about the same age (22-24 years) for periods of 10 (subject C.) and 15 days (subjects A. and B.). All the subjects were kept in a room at a temperature of between +21° and +28°. During the period of the experiment the subjects remained constantly in the horizontal position. Before the experiment the subjects received a diet of the following composition for a long period: 105 g proteins, 126 g fats, 371 g carbohydrates, calorific value 3124 kcal. During hypodynamia the diet consisted of mixed food of the following composition: 125 g proteins, 105 g fats, 307 g carbohydrates, calorific value 2745 kcal. The products were shared into four meals given at the following times: 8:30 and 11 A.M. and 3 and 8 P.M. Physiological and hygienic evaluation of the nutritional state of the subjects was based on their general condition and the study of indices of their physiological function and metabolism before the beginning of experiments lasting 10 and 15 days, during the experiment, and after their end. Gastric enzymic activity was assessed by study of the uropepsin content in the urine. The intensity of putrefaction in the intestine was judged from the excretion of indican in the urine. Metabolism was studied before, during, and after the experiments by determining the concentrations of sugar, total lipids, cholesterol, and phospholipids in the blood and total nitrogen, amino acids, urea, ammonia, creatinine, vitamins C, B₁, and B₂, 4-pyridoxic acid, and N₁-methylnicotinamide, the oxygen uptake, the concentrations of chlorides, phosphate, and calcium, the pH and the titrated acidity in the urine. Water metabolism also was studied. /357

The energy expended by the subjects was assessed mainly by a stop-watch method but in individual cases by gas analysis. The results of these investigations, indicating certain aspects of the nutritional state of the subject during hypodynamia after preceding overloading are given in Tables 1-7.

The results in Table 1 show that there was no significant difference between the uropepsin level in the subjects' urine during hypodynamia and in the initial state, and that it remained within normal limits (32-82 units/day). This demonstrated the absence of changes in enzyme function of the gastric glands on feeding with the experimental diet under the conditions used. The results of determination of indican in the urine given in Table 2 shows that there was no increase in the intensity of putrefaction in the intestine of the subjects during hypodynamia as might have been expected on the assumption that a decrease in muscular activity would be accompanied by a decrease in intestinal motor activity. The indican content in the urine remained within normal limits in every case.

The results of the investigations of protein metabolism are given in Table 3. The quantity of nitrogen excreted in the urine increased, especially during the first days of hypodynamia. A negative nitrogen balance was observed for all subjects in the initial period of hypodynamia. Excretion of other nitrogenous components in the urine was also increased: urea, ammonia and uric acid.

TABLE 1. Investigation of Gastric Enzyme Activity (Uropepsin, Units/Day: Mean Data)

Subjects	Before Experiment	During Hypodynamia
A.	74.7	58.3
B.	55.7	75.9
C.	62.4	52.9

TABLE 2. Excretion of Indican in Urine During Hypodynamia (Mean Data, mg/day)

Experiment	Before Experiment	During Hypodynamia
A.	36.6	23.19
B.	33.32	22.7
C.	46.3	27.3

The changes in nitrogen metabolism discovered in these subjects evidently depended on atrophy of muscle tissue or disturbance of protein resynthesis under hypodynamic conditions.

The results of investigation of lipid and carbohydrate metabolism under hypodynamic conditions are given in Table 4. Examination of the results in this table reveal very slight changes in the total lipid content of the blood in these subjects (normal 500-1000 mg%).

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No significant changes likewise were found in the blood cholesterol of the subjects under hypodynamic conditions when receiving the specified diet. In every case the blood cholesterol remained within normal limits (150-200 mg%), but after the experiment a slight tendency was observed for its level to increase compared with the initial state before the experiment. The concentration of lipid phosphorus in the blood remained within normal limits. The lecithin/cholesterol ratio showed a slight decrease by the end of the experiment. The results of tests performed on the subjects showed absence of significant changes in most cases in the acetone content in the urine and the blood sugar (Table 3).

The decrease in the blood sugar found in the subjects after the end of the experiment may be attributed to their considerable utilization of carbohydrates because of increased mobility.

The results of determination of the excretion of certain vitamins and their derivatives in the subjects' urine are given in Table 5. The comparatively low supplies of these vitamins in the subjects will be noted. After the subjects had received the experimental diet for a long period, the supply of vitamin C to the body improved sharply and the excretion of ascorbic acid in the urine remained high throughout the experiment. The thiamine level in the body fell slightly under hypodynamic conditions, mainly on the last days of the experiment.

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A similar decrease in the vitamin B₂ level in the body was also observed. Conversely, the supply of vitamin PP was adequate. The initial level of supply of vitamin B₆ to the subjects, as shown by the study of 4-pyridoxic acid excretion, was low and remained at that level throughout the experiment.

TABLE 3. Excretion of Some End Products of Protein Metabolism in the Urine Per Day
(Mean Data, g)

Subject	Experimental Conditions	Nitrogen Intake with the food	Excretion in Urine				
			Total Nitrogen	Urea	Ammonia	Amino Nitrogen	Uric Acid
A.	Initial Background	16,8	15,3	10,19	0,854	0,363	0,855
	During Hypodynamia	16,69	17,0	13,25	0,785	0,528	1,125
B.	Initial Background	16,8	16,4	12,32	0,85	0,466	0,77
	During Hypodynamia	16,62	17,0	13,2	1,27	0,545	1,178
C.	Initial Background	16,8	15,5	10,5	0,68	0,304	0,94
	During Hypodynamia	16,0	16,1	13,0	0,938	0,406	1,075

Commas represent decimal points.

With a standardized diet and uniform activity, the gas exchange and acid-base balance are known to remain constant within limits. This led us to study the action of hypodynamia on these indices of the general trend of metabolic processes in the body. The results are given in Table 6. The mean values of pH and titrated acidity of the urine given in this table show that the experimental conditions and diet had no effect on these indices: only very slight changes were found and both pH and titrated acidity remained within normal limits. The results of investigation of the gas exchange showed that on the days of hypodynamia there was a slight decrease in pulmonary ventilation, oxygen consumption and excretion of CO₂. The respiratory quotient showed no significant change. The energy expenditure of all subjects on days of hypodynamia fell on the average by 10%. The results of investigations of water and salt metabolism are given in Table 7. They show that the mean excretion of calcium and phosphorus in the 24-hour urine was higher under hypodynamic conditions than when muscle activity was unrestricted. In the case of subjects A. and B., the excretion of calcium in the urine reached a maximum on one day in the period of hypodynamia. Excretion of phosphorus in the urine of subjects A. and B. did not exceed 1.02-1.04 g/day during the experiment.

As an index of the subjects' nutritional state, their body weight remained practically at the same level throughout the experiment. The body temperature also remained unchanged. The volume of water drunk during the day increased as the experiment continued; the diuresis fell slightly. This was evidently associated with an increase in extrarenal loss of water. The effect of overloading was studied on individual aspects of metabolism. The results of investigations carried out on a day during which the subjects were exposed to overloads showed no significant change in the indices of nitrogen, carbohydrate, lipid, water and salt metabolism.

TABLE 4. Dynamics of Indices of Lipid and Carbohydrate Metabolism (Mean Data, mg%)

Subjects	Before Experiment					During Hypodynamia					After Experiment				
	Total Lipids	Choles-terol	Lipid Phos-phorus	Lecithin/Choles-terol	Sugar	Choles-terol	Lipids Phos-phorus	Lecithin/Choles-terol	Sugar	Total Lipids	Choles-terol	Lipid Phos-phorus	Lecithin/Choles-terol	Sugar	
A.	920	136	7,40	1,3	101	135	6,30	1,1	109	1020	154	7,22	1,1	82	
B.	950	153	7,86	1,2	107	158	5,96	0,95	104	1000	164	6,61	1,0	84	
C.	530	142	8,52	1,5	100	188	7,19	0,90	100	500	177	6,89	0,9	75	

TABLE 5. Dynamics of Metabolic Indices of Certain Vitamins in Subjects Differing in Character of Activity and Diet

Daily Excretion of Vitamins with Urine	Before Experiment	Hypodynamia, Days														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
B ₁ , μ g . .	90,00	146	69	71	133	53	22	86	107	109	103	61	71	68	63	47
B ₂ , μ g . .	89,00	89	51	51	68	46	48	47	94	106	49	81	72	114	56	57
N ₁ -Methyl-nicotinamide	3,92	6,5	3,3	6,6	5,3	6,0	7,2	6,3	7,2	13,2	6,8	4,2	6,1	8,2	7,2	7,6
4-Pyridoxic acid, μ g .	720,00	1014	518	797	483	582	661	601	812	836	974	673	833	1188	621	705
C, mg. . .	15,3	15,4	6,1	7,3	13,2	13,0	9,08	15,77	8,48	19,11	18,76	28,64	13,90	26,24	15,30	18,53

NOTE: Commas represent decimal points.

TABLE 6. Indices of Acid-Base Balance and Gas Exchange Under Different Conditions of Activity and Diet

Subjects	Before Experiment							
	pH	Titrated Acidity	Pulmonary Ventilation, Liters/Min.	Excretion of CO ₂ , Liters/ Min.	O ₂ Consump- tion, Liters/ Min.	Respiratory Quotient	Energy Expenditure Per Day, Kcal	
							Actual	Cal- culated
A.	6,44	1,55	6,6	0,238	0,28	0,83	1944	1954
B.	7,00	1,42	7,3	0,22	0,24	0,82	1670	1622
C.	6,58	1,43	6,5	0,195	0,255	0,76	1728	1680

Conclusion

Subjects	During Hypodynamia							
	pH	Titrated Acidity	Pulmonary Ventilation, Liters/Min.	Excretion of CO ₂ , Liters/ Min.	O ₂ Consump- tion, Liters/ Min.	Respiratory Quotient	Energy Expenditure Per Day, Kcal	
							Actual	Cal- culated
A.	6,35	1,48	6,00	0,20	0,24	0,83	1670	1954
B.	6,07	1,73	6,2	0,20	0,23	0,84	1497	1622
C.	5,98	1,61	6,0	0,18	0,22	0,81	1512	1680

Commas represent decimal points.

TABLE 7. Dynamics of Some Indices of Water and Salt Metabolism Under Hypodynamic Conditions (Mean Data)

Subjects	Before Experiment			Hypodynamia		
	Diuresis, ml	Ca, mg/day	P, g/day	Diuresis, ml	Ca, mg/day	P, g/day
A.	1080	182	0,85	948	220	1,02
B.	1160	146	0,97	975	219	1,03
C.	1704	233	1,02	1170	263	1,08

Commas represent decimal points.

Results showing the effects of overloads on vitamin metabolism of the subjects are given in Table 8. A sharp decrease in the excretion of vitamin C during overloading will be apparent. It may be assumed that the ascorbic acid balance remained favorable because of the high content of this vitamin in the diet and also because of the low consumption of the vitamin as a result of the state of hypodynamia. This is confirmed by the response to overloading. High values of ascorbic acid excretion from the body were due to the considerable intake of the vitamin with blackcurrant juice, administered regularly to the subjects. Excretion of vitamin B₁ with the urine fell in response to the action of overloading. The vitamin B₆ excretion fell in a similar manner. The results given in Table 8 also indicate that overloading must be taken into account when the factors of space flight are studied.

TABLE 8. Effect of Overloading on Indices of Metabolism of Certain Vitamins in Subjects Differing in Diet and Character of Activity

Excretion in Urine Per Day	Before Hypodynamia			After Hypodynamia		
	Before Expo- sure to Over- loading	During Over- loading	After Over- loading	Before Expo- sure to Over- loading	During Over- loading	After Over- loading
Vitamin B ₁ , μ g	90	67	100	47	29	56
Vitamin B ₂ , μ g	89	62	81	57	39	84
N ₁ -Methylnicotinamide, mg	3,92	2,87	2,38	7,6	2,8	3,17
4-Pyriodoxic Acid, μ g	720	365	566	705	303	994
Vitamin C, mg.	15,3	12,2	11,9	185,3	38,0	26,5

Commas represent decimal points.

The investigation of some aspects of the nutritional state during hypodynamia lasting for 10-15 days and preceded by overloading revealed changes in metabolism of the subjects receiving the diet described above which can be described briefly as follows: 1) the enzyme function of the gastric glands remained essentially unchanged; 2) in a state of hypodynamia, because of lowered metabolism in the muscle tissue, the excretion of urea, ammonia, amino acids and uric acid in the urine was increased; 3) the principal indices of lipid metabolism (total lipids, cholesterol, lipid phosphorus in the blood, acetone content in the urine) remained within normal limits in the subjects and showed no significant change under hypodynamic conditions; 4) the blood sugar remained within normal limits but after the end of the experiment a decrease in the blood sugar concentration was observed in these subjects; 5) some indices of acid-base balance (titrable acidity of the urine, pH) remained within normal limits during hypodynamia; 6) the excretion of calcium and phosphorus in the urine increased;

7) the supply of vitamins PP and C was adequate during hypodynamia, while that of vitamins B₁, B₂ and B₆ was lowered; 8) the energy expenditure of the subjects fell slightly during the experiment with hypodynamia; 9) on the days of hypodynamia the indices of gas exchange (pulmonary ventilation, oxygen consumption, CO₂ excretion) were lowered, but the respiratory quotient remained almost unchanged.

The diet investigated, generally speaking, proved adequate in its nutritional value and content of basic food substances for the subjects kept under hypodynamic conditions preceded by overloading, with the exception of its content of certain vitamins.

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USE OF A BIOMASS OF UNICELLULAR ALGAE FOR HUMAN FEEDING

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Judging from its chemical composition, a biomass of unicellular algae must have high nutritive value [1, 2]. The chemical composition of the biomass depends on cultivation conditions and varies within the following limits: proteins 8.7-88.2, fats 4.5-85.6, carbohydrates 5.7-37.5, ash 3-4% [11]. However, the specific taste and smell of the algal biomass hamper its use for human feeding.

By treatment with alcohols (methanol, butanol, etc.), the algae lose their specific taste, become pale grey in color, and are more palatable than in their untreated condition [6].

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The results of degustation tests on products containing algal biomass (*Chlorella*) have been described in a number of papers [4, 5, 7-9]. Pastries and bread, cooked meat balls, hamburgers, stuffed eggs, Japanese vermicelli soup, ice cream, jellies, and pastes for sandwiches have obtained organoleptic approval. Algae were added to these dishes in the proportion of 5-10%, except for the sandwich paste which contained 75% of algae.

American workers [14] consider that the specific taste of algae is less perceptible in confections such as gingerbread and chocolate cookies or cakes.

Tamura and co-workers [14] determined the assimilation of protein of unicellular algae included in the composition of cakes used in the diet to the extent of 21-23 g (dry weight) daily. They found that algal proteins are assimilated less readily than rice proteins, but the rate of assimilation of fats and carbohydrates was not reduced [15].

Hayami and co-workers [5] tested the assimilation of algal biomass, blanched and decolorized with methanol and given for four days to five women whose diet included 30 g dried algae. Assimilation of protein of the decolorized biomass was greater (86.3%) than that of untreated biomass (74.8%).

Miyoshi [10] included about 30 g algae in the diet of two men. He found that during the period when algae were given in diet the stools of the subjects became dark and fluid, and increased in amount compared with the control period. Compared with initially, the subjects lost a certain amount of weight.

American workers [12] added different quantities of biomass of unicellular algae to human food. The algae were blanched and dried *in vacuo*. Before the experiment they were autoclaved for 2 h at 160°. Experiments were carried out on five men aged from 18-23 years, with a mean body weight of 71.4 kg (from 63 to 90.5 kg). The investigation continued for 40 days and was divided into 7 periods. The first period (5 days) was the control. The second, third and

fourth periods each lasted six days. During this time dried algae were added to the basic diet at the rate of 10, 20, and 50 g for each subject daily. The 5th and 6th periods each lasted 3 days. During this time algae were added to the basic diet at the rate of 100 and 200 g, respectively. These two periods were separated by an interval of four days when the subjects received the basic diet. The 7th period lasted 2 days and followed immediately after the 6th without an interval. Depending on the dose of added algae, the basic diet was varied to keep its protein content and calorific value constant. In the 7th period, however, the protein content was twice as high as in the control period although the calorific value was slightly lower. This was because the diet consisted only of dried algae (500 g per person per day) with water and a small quantity of fruit syrup added to improve flavor. In the experimental periods the subjects were given gingerbread and chocolate cookies and cakes to which up to 25% of dried algae were added before cooking, and also a mixture of dried algae with cold milk and water in a concentration of 75 g per glass.

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On the first days the subjects noticed the strong and unpleasant taste of the algae in the experimental dishes, but after a few days they became accustomed to it. When algal biomass was taken at the rate of 10-20 g daily, the subjects developed flatulence, gases accumulated in the intestine and the abdomen became distended. The stools became dark green in color on the second day of the experimental period and remained colored until algae were excluded from the diet. When the daily dose of dried algae was 50 g, intestinal peristalsis increased and the stools became abundant and dry. On the whole the subjects tolerated addition of up to 100 g algae to the daily ration relatively well. With a dose of 200 g algae in the daily ration, the symptoms mentioned above became more marked. Nausea also appeared. One subject complained of diffuse spasmodic abdominal pain and continuous vomiting. In the 7th period three subjects took part in the experiments. One gave up because he felt unwell, but the other two survived the 2-day period in spite of nausea, weak spasmodic abdominal pain, headache and general malaise. During the whole investigation the subjects lost from 1-2 kg in weight. The daily weight of the stools was doubled during the last two periods of the experiment. The moisture content in the stools fell from 75 to 65%, while their ash, fat, nitrogen and carbohydrate content increased when the subjects received a diet with high concentration of algae, indicating a decrease in its assimilation.

Since a diet with the addition of algae is not a customary one for man, its toxicity was investigated. The subjects were kept under medical observation for six months and no signs of toxicity of the algae were found.

In a leper colony in Venezuela [3] observations were made on patients who received unicellular algae in their diet for between one and three years. Observations were made on 37 persons aged from 8 to 20 years, 26 persons aged from 20-40 years, and 17 aged from 40-70 years. Dry algal biomass (*Chlorella*) was added to soup at the rate of 10 g for children and 15 g for adults. The patients ate their soup without distaste. They gained in weight and stated that they felt some improvement.

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The composition of the intestinal microflora was studied in persons receiving blanched algal biomass (*Chlorella*) in their diet. Japanese investigators [13] investigated the intestinal microflora of five women aged 21-22 years receiving

30 g blanched algae daily for 10 days in cookies and ice cream. They observed some changes in the content of Escherichia coli and Lactobacillus acidophilus. However, these changes were not consistent in character. American workers [12] report that the E. coli population and the total number of bacteria homogenates of the subjects' stools showed no significant change even when algae was added to the daily diet at the rate of 500 g.

As this survey of the literature shows, a biomass of unicellular algae has no toxic action on man.

Investigations were therefore carried out to study the effect of diets including different quantities of algal biomass (a mixture of Chlorella and Scenedesmus) on some aspects of human metabolism. The maximal quantity of algal biomass which can be included in the human diet was also determined. Three investigations were carried out in which dry biomass was added to the diet at the rate of 50, 100, and 150 g. The algal biomass used was dried lyophilically and had the following chemical composition, expressed relative to the dried substance: protein 51, fat 12, carbohydrates 23, cellulose 5, ash 9%. The biomass of algae used in these investigations was not washed to remove the culture medium.

The chemical composition of the diets was as follows: protein 116-121 g, fat 100-107 g, carbohydrate 460-490 g; calorific value 3360-3440 kcal. Algae were added as jellies prepared in gelatin and agar-agar, a blancmange made with starch, and drinks made with the addition of sugar, raisins, lemon juice, coffee, and vanillin.

The experiments were carried out on 12 volunteers, clinically healthy men aged from 23-39 years, weighing initially 54-100 kg, and 165-184 cm in height.

The subjects performed their normal work.

During the first investigation, when 50 g biomass of unicellular algae was added to the daily diet, three subjects (A., K., and T.) took part, in the second investigation four subjects (M., V., I. and Sh.) received 100 g algae daily, and in the third investigation five subjects (S., Z., E., P. and G.) each received 150 g algae daily. Except for two who had to give up before the end because of their state of health, the subjects received the algal diet for 20-23 days.

Before the beginning and after the end of the investigations, the subjects receiving algae were given a clinical examination. A medical check was applied every day, and the body weight and temperature and the pulse rate determined. Once every ten days, starting with the second investigation, an additional cardiovascular function test together with manual and spinal dynamometry and spirometry was carried out.

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Once during the control investigations and twice in the experimental periods the nonprotein nitrogen, urea, ammonia, cholesterol and phospholipids were determined in the venous blood. The 24-hour volume, specific gravity, pH, total nitrogen, urea, ammonia, creatine, creatinine, amino-acid nitrogen, and 17,21-dihydroxy-20-ketocorticosteroids in the urine were determined. Moisture content, total nitrogen, fat, ash, and carbohydrates in the stools were estimated. The subjects noted the volume of water they drank and their 24-hour diuresis. Each subject kept a daily diary in which he recorded how he felt and his assessment of the diet and the daily events.

On the first days of receiving a diet including 50 g algae, subject A, felt dyspeptic symptoms such as flatulence with the smell of algae, nausea, loss of appetite and meteorism. These symptoms disappeared after two days. The dyspeptic manifestations were much less marked in the subjects K. and T. Subsequently all subjects became accustomed to the diet and made no complaints.

All subjects receiving a diet with 100 g algal biomass noticed certain dyspeptic disorders for the first few days (flatulence, meteorism, loss of appetite). Subsequently subjects M., V. and I. felt well until the end of the investigations, although V. and I. had no appetite for dishes containing algae. The subject Sh. had to make an effort in order to eat dishes containing algae before the end of the investigation. No abnormalities of the gastro-intestinal tract were found in this subject.

The subjects responded differently to a diet including 150 g of algal biomass. Subject G. ate dishes containing algae without difficulty throughout the period of investigation, and made no complaints. Subject Z. also tolerated dishes containing algae well, but on the 14th day developed edema of the right eyelids, nose, and frontal region, becoming more severe toward evening, despite an intravenous injection of 10 ml 10% calcium chloride and administration of dimedrol during the afternoon. Next morning the edema spread over the whole face, the right eye could not be opened, and petechial hemorrhages were present on the nose and frontal region. Nevertheless, subject Z.'s general condition was good and he expressed his willingness to continue the investigation. However, he was withdrawn from the investigation and admitted to hospital.

On admission to hospital his general condition was satisfactory. The skin of the face was pale. Marked and firm edema was present in the frontal region, eyelids, nose, cheeks, submandibular region and upper part of the neck on the right side. The fingers were moderately edematous and petechial hemorrhages occurred in the skin of the nose and forehead. Pulse rate 66/min, volume good, blood pressure 110/80 mm Hg.

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The following treatment was given in hospital: No. 5 diet, cleansing enemas, saline laxatives, dimedrol and rutin orally, ascorbic acid and magnesium intra-muscularly, and calcium chloride intravenously.

On the second day of hospitalization clinical investigations gave the following results: blood formula normal, ESR 3 mm in 1 h, total blood bilirubin 1.37 mg%, cholesterol 206 mg%, thymol test 11 units, mercuric chloride test 2.0, blood sugar 125 mg%. Urine analysis: sp. gr. 1020, reaction acid, protein and sugar absent. Sediment normal. Analysis of stools: test for blood negative. Analysis of gastric juice: total fasting acidity 15, free acidity 0. At the height of digestion, total acidity 25, free acidity 4. Fluoroscopy of the chest and gastro-intestinal tract showed no abnormality. After five days in hospital, subject Z. was transferred to the control diet, which he continued to take until the end of the investigation.

Subject P. reported dyspeptic symptoms (meteorism, loss of appetite) while still on the control diet. After transfer to the experimental diet the dys-

peptic symptoms increased: stools were passed frequently and he disliked the dishes containing algae. He tolerated the drinks containing algae better than the jellies. On the 12th day of receiving the diet with algae, subject P. began to notice slight "cold pricking" on the right hand. On the 15th day a dark band was seen at the edge of the right thumbnail. On the 16th day, the right eyelid and the dorsal surface of the fingers began to itch. The right eyelids were slightly edematous. Because of the appearance of signs of edema, the subject was put back on the control diet. Despite this, next day he noticed slight burning on the dorsal surface of the hand and fingers, especially the right. The skin of the fingers gave an increased reaction to heat (warm water appeared hot). The edema on the face and hands increased. These phenomena persisted for 4 days. On the 5th day the edema of the face and hands diminished. By the 10th day after discontinuing the diet with algae, all these signs had disappeared. Only slight peeling of the skin over the fingers remained.

Throughout the investigation this subject felt well. Apart from the phenomena mentioned above, no other abnormalities affecting the subject's health were observed.

Subject G. developed cyanosis under the nails of the second and third toes and along the medial border of the right foot as far as the base of the big toe 16 days after receiving the experimental diet. The toes were edematous and painful during walking. These phenomena disappeared after two weeks.

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Subject E. felt a burning sensation in the region of the right big toe 35 days after the end of the investigation. Slight puffiness was found on the medial border of the right foot, including the big toe. The skin of this region was slightly red in color (petechial hemorrhages were seen). These phenomena disappeared after 4 days. Subject S. showed no abnormality affecting his state of health when taking the diet including algae.

Regardless of differences in the content of algae in the diet, all subjects showed an increase in the blood nonprotein nitrogen on the 10th day up to 70-90 mg%, falling to the initial level by the 20th day of the investigation. This can be interpreted as adaptation to the diet containing algae by the 20th day of the investigation. The blood cholesterol of most subjects increased until the 20th day and then fell when the subjects returned to the control diet. In 2 subjects no decrease in the blood cholesterol level was observed 10 days after the diet containing algae was discontinued. The blood cholesterol remained unchanged in one subject throughout the investigation. Since a distinct increase in the blood cholesterol did not take place immediately in these subjects, but on the 20th day after starting to take the algal diet, it can be postulated that these changes were not produced by phytosterols of the algae but by the action of the biomass as a whole on cholesterol metabolism in the body. The changes in the blood concentration of phospholipids in most subjects were identical to changes in the cholesterol level. The other indices investigated were within normal physiological limits. All the subjects remained under medical observation for more than one year and no abnormalities affecting their health were observed.

Pathological changes such as edema and petechial hemorrhages have not been observed by other investigators, probably because of the smaller amount

of algal biomass given in the experimental diets, the shorter periods of investigation, or differences in chemical composition of the diet. These pathological changes, presumably of allergic character, may have been due to components of the culture medium or to other biologically active substances present in the composition of the algae (proteins, carotenoids, the antibiotic chlorellin, and so on).

Further investigations to discover the causes of these abnormalities are in progress at the present time.

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MATHEMATICAL METHOD FOR CALCULATING NECESSARY QUANTITY OF PRODUCTS FOR A GIVEN DIET USING A LIMITED ASSORTMENT OF PRODUCTS

M. F. Fomin

One of the main problems associated with space flights of long duration is that of feeding the spacecraft crew.

One aspect of this problem is the composition of the diet. The diet of the spacecraft crew must not only be of appropriate calorific value, but it must also contain specified amounts of proteins, fats and carbohydrates. Different products contain these components in different proportions, and they may be used in different amounts when diets are drawn up. The same diet of specified composition may be obtained from a different range of products, and changes in qualitative composition of the products used will result in quantitative changes in each product. There is thus a need for mathematical relationships to be deduced, by means of which a diet of specified composition and calorific value can be easily selected using an available assortment of products. /371

Furthermore, if a diet and a definite assortment of products which may be provided on a spacecraft are specified, by using these mathematical relationships and drawing up hypothetical menus for the specified diet, the quantities of each product consumed can be determined.

The quantitative consumption of each hypothetical product, determined in this manner, can be used to calculate the sowing areas of the various crops, the necessary number of animals, and the reserves of products in the spacecraft.

In this paper a possible method which can be used to calculate a specified diet is presented to the reader.

DEFINITION OF THE PROBLEM

In order to calculate a diet of specified composition consisting of proteins, fats and carbohydrates, it is first necessary to determine the quantity of these components required in the diet. This can be done most conveniently on the basis of the required calorific value of the diet and the ratio between proteins (P), fats (F) and carbohydrates (C).

Suppose we need a diet with calorific value Q kcal and with proteins, fats, and carbohydrates in the following ratio:

$$P : F : C : = \alpha : \beta : \gamma. \quad (1)$$

Knowing the coefficients of conversion of weight of proteins, fats, and carbohydrates into calories (4.1, 9.3 and 4.1 kcal/g, respectively), we have the equation:

$$Q = 4.1B + 9.3F + 4.1C, \quad (2)$$

where B, F and C represent the weights of proteins, fats and carbohydrates, respectively, expressed in grams.

Using Eqs. (1) and (2), we can determine the values of P, F and C, which are expressed by the following equations:

$$\begin{aligned} P &= \frac{Q \cdot \alpha}{(4.1\alpha + 9.3\beta + 4.1\gamma)}; \\ F &= \frac{Q \cdot \beta}{(4.1\alpha + 9.3\beta + 4.1\gamma)}; \\ C &= \frac{Q \cdot \gamma}{(4.1\alpha + 9.3\beta + 4.1\gamma)}. \end{aligned} \quad (3)$$

If the required calorific value of the diet and the relative proportions of proteins, fats and carbohydrates in it are known or specified, the Eqs. (3) can be used to determine the quantity of each component in grams.

Often when a diet is calculated, besides specified relative proportions of proteins, fats and carbohydrates, the proportion of proteins must be subdivided into proteins of vegetable (VP) and animal (AP) origin and the proportion of fats into fats of vegetable (VF) and animal (AF) origin, respectively. /372

In this case, having the values of P, F and C calculated by the Eqs. (3), we can determine VP and AP, and VF and AF by using the essential relative proportions specified either as percentages or fractions.

The problem is thus to draw up a diet from available products with specified relative proportions of proteins, fats and carbohydrates and with a specified calorific value.

Let us assume that, for a specified calorific value of the diet and for specified relative proportions of proteins, fats and carbohydrates (including those of vegetable and animal origin) we need to have in the products used for the diet a grams of carbohydrates (C) b grams of fats of vegetable origin (VF), c grams of fats of animal origin (AF), d grams of proteins of vegetable origin (VP) and e grams of proteins of animal origin (AP).

We also have a series of products with known percentage contents of proteins, fats and carbohydrates which can be used in the diet. These products are given below, for convenience, in a scheme in which the percentage content of C, VF, AF, VP and AP of each product is denoted by the corresponding letters p, m, q, r and s with indices of the corresponding product.

For example: p_A represents the percentage content of carbohydrates in product A; m_B represents the percentage content of vegetable fats in product B.

With these initial data available, we need to determine the quantity of each product A, B, C, D, E, F, G and H [or some of these products] (in grams) for the specified diet.

Product g	Content				
	C	VF	AF	VP	AP
A	p_A	m_A	q_A	r_A	s_A
B	p_B	m_B	q_B	r_B	s_B
C	p_C	m_C	q_C	r_C	s_C
D	p_D	m_D	q_D	r_D	s_D
E	p_E	m_E	q_E	r_E	s_E
F	p_F	m_F	q_F	r_F	s_F
G	p_G	m_G	q_G	r_G	s_G
H	p_H	m_H	q_H	r_H	s_H
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
N	p_N	m_N	q_N	r_N	s_N

SOLUTION

To solve the problem equations must be formed using all the initial data. To begin with, knowing the percentage content of the components (C; VF; AF; VP; AP) of each product we can determine the number of grams of each component in each product taken. /373

Let us conventionally denote the number of grams of the component taken in each product by the letter of the product with an index consisting of the initial letter of the component, for example: A_C for the number of grams of carbohydrates in A grams of the product; B_{AP} for the number of grams of animal protein in B grams of product; and so on.

In that case, starting from the data in Table 1 and taking into consideration the remarks made above, we have the following expressions:

$$\left. \begin{aligned}
 A_C &= \frac{A \cdot p_A}{100}; A_{VF} = \frac{A \cdot m_A}{100}; A_{AF} = \frac{A \cdot q_A}{100}; A_{VP} = \frac{A \cdot r_A}{100}; \\
 &A_{AP} = \frac{A \cdot s_A}{100} \\
 B_C &= \frac{B \cdot p_B}{100}; B_{VF} = \frac{B \cdot m_B}{100}; B_{AF} = \frac{B \cdot q_B}{100}; B_{VP} = \frac{B \cdot r_B}{100}; \\
 &B_{AP} = \frac{B \cdot s_B}{100} \\
 C_C &= \frac{C \cdot p_C}{100}; C_{VF} = \frac{C \cdot m_C}{100}; C_{AF} = \frac{C \cdot q_C}{100}; C_{VP} = \frac{C \cdot r_C}{100}; \\
 &C_{AP} = \frac{C \cdot s_C}{100} \\
 D_C &= \frac{D \cdot p_D}{100}; D_{VF} = \frac{D \cdot m_D}{100}; D_{AF} = \frac{D \cdot q_D}{100}; D_{VP} = \frac{D \cdot r_D}{100}; \\
 &D_{AP} = \frac{D \cdot s_D}{100}
 \end{aligned} \right\} (4)$$

$$\begin{array}{l}
E_C = \frac{E \cdot p_E}{100}; E_{VF} = \frac{E \cdot m_E}{100}; E_{AF} = \frac{E \cdot q_E}{100}; E_{VP} = \frac{E \cdot r_E}{100}; \\
E_{AP} = \frac{E \cdot s_E}{100} \\
\vdots \\
N_C = \frac{N \cdot p_N}{100}; N_{VF} = \frac{N \cdot m_N}{100}; N_{AF} = \frac{N \cdot q_N}{100}; N_{VP} = \frac{N \cdot r_N}{100}; \\
N_{AP} = \frac{N \cdot s_N}{100}
\end{array} \quad \left. \begin{array}{l} \\ \\ \\ \\ \end{array} \right\} \begin{array}{l} \text{(cont'd)} \\ (4) \end{array}$$

From the conditions of the problem we know the quantity of proteins, fats and carbohydrates required in the diet, and also the quantity of these components contained in each product. On the basis of these facts we can form the equations: /374

$$\left. \begin{array}{l}
a = A_y + B_y + C_y + D_y + E_y + F_y + \dots + N_C \\
b = A_{VF} + B_{VF} + C_{VF} + D_{VF} + \\
\quad + E_{VF} + F_{VF} + \dots + N_{VF} \\
c = A_{AF} + B_{AF} + C_{AF} + D_{AF} + \\
\quad + E_{AF} + F_{AF} + \dots + N_{AF} \\
d = A_{VP} + B_{VP} + C_{VP} + D_{VP} + \\
\quad + E_{VP} + F_{VP} + \dots + N_{VP} \\
e = A_{AP} + B_{AP} + C_{AP} + D_{AP} + \\
\quad + E_{AP} + F_{AP} + \dots + N_{AP}
\end{array} \right\} (5)$$

After consideration of the expressions (4), the system of equations (5) will assume the following form:

$$\left. \begin{array}{l}
a = \frac{p_A}{100} A + \frac{p_B}{100} B + \frac{p_C}{100} C + \frac{p_D}{100} D + \\
\quad + \frac{p_E}{100} E + \frac{p_F}{100} F + \dots + \frac{p_N}{100} N \\
b = \frac{m_A}{100} A + \frac{m_B}{100} B + \frac{m_C}{100} C + \frac{m_D}{100} D + \\
\quad + \frac{m_E}{100} E + \frac{m_F}{100} F + \dots + \frac{m_N}{100} N \\
c = \frac{q_A}{100} A + \frac{q_B}{100} B + \frac{q_C}{100} C + \frac{q_D}{100} D + \\
\quad + \frac{q_E}{100} E + \frac{q_F}{100} F + \dots + \frac{q_N}{100} N \\
d = \frac{r_A}{100} A + \frac{r_B}{100} B + \frac{r_C}{100} C + \frac{r_D}{100} D + \\
\quad + \frac{r_E}{100} E + \frac{r_F}{100} F + \dots + \frac{r_N}{100} N
\end{array} \right\} (6)$$

$$e = \frac{s_A}{100}A + \frac{s_B}{100}B + \frac{s_C}{100}C + \frac{s_D}{100}D + \frac{s_E}{100}E + \frac{s_F}{100}F + \dots + \frac{s_N}{100}N \quad \left. \vphantom{\frac{s_A}{100}A} \right\} \begin{array}{l} \text{(cont'd)} \\ (6) \end{array}$$

For convenience in using system (6), we multiply both parts of the equations of this system by 100, and thus obtain /375

$$\left. \begin{array}{l} 1) 100a = p_A A + p_B B + p_C C + p_D D + p_E E + p_F F + \dots + p_N N \\ 2) 100b = m_A A + m_B B + m_C C + m_D D + m_E E + m_F F + \dots + m_N N \\ 3) 100c = q_A A + q_B B + q_C C + q_D D + q_E E + q_F F + \dots + q_N N \\ 4) 100d = r_A A + r_B B + r_C C + r_D D + r_E E + r_F F + \dots + r_N N; \\ 5) 100e = s_A A + s_B B + s_C C + s_D D + s_E E + s_F F + \dots + s_N N \end{array} \right\} (7)$$

Hence, from the specified conditions we have obtained a system of five equations with n unknowns (A, B, C, D, E, F, ... N). When the number of unknowns is greater than the number of linearly independent equations, the system has an infinite number of solutions, and these solutions may be both positive and negative.

We are interested only in the nonnegative solutions of the system.

Finding the nonnegative solution of the system means finding solutions for which the values of all unknown quantities are equal to zero or greater than zero, i. e., in our present case to satisfy the condition:

$$A \geq 0; B \geq 0; C \geq 0; D \geq 0; E \geq 0; \dots; N \geq 0.$$

To find nonnegative solutions of the system of equations (7), we must adhere to the following order:

1. Transcribe the system of equations (7) in the form of a system of null-equations, which will have the following form:

$$\left. \begin{array}{l} 1) 0 = 100a - (p_A A + p_B B + p_C C + p_D D + p_E E + p_F F + \dots + p_N N) \\ 2) 0 = 100b - (m_A A + m_B B + m_C C + m_D D + m_E E + m_F F + \dots + m_N N) \\ 3) 0 = 100c - (q_A A + q_B B + q_C C + q_D D + q_E E + q_F F + \dots + q_N N) \\ 4) 0 = 100d - (r_A A + r_B B + r_C C + r_D D + r_E E + r_F F + \dots + r_N N) \\ 5) 0 = 100e - (s_A A + s_B B + s_C C + s_D D + s_E E + s_F F + \dots + s_N N) \end{array} \right\} (8)$$

2. Select the basis unknowns (basis products), relative to which the system of equations should be solved. The number of basis unknowns must be equal to the number of equations. In our case there are five basis unknowns, for example, A, B, C, D, E.

3. Choose one of the basis unknowns for which the coefficients are positive (in one or several equations of the system); let us take, for example, the basis unknown A.

In null-equations the coefficients are considered to be positive if they are positive inside brackets.

4. Find the minimal value of the quotients obtained by dividing the free terms by the corresponding (positive only) coefficients for the selected unknown.

For example, if A is the unknown, let the coefficients in all the equations be positive, in which case the quotients obtained by dividing free terms by coefficients relative to A will have the values:

$$\frac{100a}{p_A}; \frac{100b}{m_A}; \frac{100c}{q_A}; \frac{100d}{r_A}; \frac{100e}{s_A}$$

and of these, let the quotient $100a/p_A$ have the least value.

5. Solve relative to the chosen basis unknown the null-equation in which the quotient obtained by dividing the free term by the coefficient of the chosen unknown has the least value.

In our example, having chosen A as the basis unknown, the quotient $100a/p_A$ has the least value and it applies to null-equation 1 of system (8), so that we may solve this null-equation with respect to A.

$$A = \frac{100a}{p_A} - \left(\frac{p_B}{p_A} B + \frac{p_C}{p_A} C + \frac{p_D}{p_A} D + \frac{p_E}{p_A} E + \frac{p_F}{p_A} F + \dots + \frac{p_N}{p_A} N \right). \quad (9)$$

6. Substitute in the remaining null-equations of system (8) the expression for the solved basis unknown.

In our example we substitute expression (9) into null-equations 2, 3, 4 and 5 of system (8).

After substitution we have the following null-equations:

$$\left. \begin{aligned} 1) \quad 0 = 100b - m_A \frac{100a}{p_A} - \left[\left(m_B - m_A \frac{p_B}{p_A} \right) B + \right. \\ \left. + \left(m_C - m_A \frac{p_C}{p_A} \right) C + \left(m_D - m_A \frac{p_D}{p_A} \right) D + \left(m_E - m_A \frac{p_E}{p_A} \right) E + \right. \\ \left. + \dots + \left(m_N - m_A \frac{p_N}{p_A} \right) N \right]; \end{aligned} \right\} \quad (10)$$

$$\begin{aligned}
2) \quad 0 &= 100c - q_A \frac{100a}{p_A} - \left[\left(q_B - q_A \frac{p_B}{p_A} \right) B + \right. \\
&+ \left(q_C - q_A \frac{p_C}{p_A} \right) C + \left(q_D - q_A \frac{p_D}{p_A} \right) D + \left(q_E - q_A \frac{p_E}{p_A} \right) E + \\
&\quad \left. + \dots + \left(q_N - q_A \frac{p_N}{p_A} \right) N \right]; \\
3) \quad 0 &= 100d - r_A \frac{100a}{p_A} - \left[\left(r_B - r_A \frac{p_B}{p_A} \right) B + \right. \\
&+ \left(r_C - r_A \frac{p_C}{p_A} \right) C + \left(r_D - r_A \frac{p_D}{p_A} \right) D + \\
&\quad \left. + \left(r_E - r_A \frac{p_E}{p_A} \right) E + \dots + \left(r_N - r_A \frac{p_N}{p_A} \right) N \right]; \\
4) \quad 0 &= 100e - s_A \frac{100a}{p_A} - \left[\left(s_B - s_A \frac{p_B}{p_A} \right) B + \right. \\
&+ \left(s_C - s_A \frac{p_C}{p_A} \right) C + \left(s_D - s_A \frac{p_D}{p_A} \right) D + \\
&\quad \left. + \left(s_E - s_A \frac{p_E}{p_A} \right) E + \dots + \left(s_N - s_A \frac{p_N}{p_A} \right) N \right].
\end{aligned}
\tag{10}$$

7. From the null-equations (10) thus obtained, in a similar manner we find the next basis unknown and substitute its expression both in the unused null-equations and in the expressions of the previously solved basis unknowns (in our example in expression (9) for A). /377

We carry out such operations until we have all the expressions for the basis unknowns which contain only a free term and nonbasis unknowns.

In our example the expression will have the form:

$$\begin{aligned}
A &= Q_A - f_A(F, G, H, \dots, N.) \\
B &= Q_B - f_B(F, G, H, \dots, N.) \\
C &= Q_C - f_C(F, G, H, \dots, N.) \\
D &= Q_D - f_D(F, G, H, \dots, N.) \\
E &= Q_E - f_E(F, G, H, \dots, N.),
\end{aligned}
\tag{11}$$

where Q_A, Q_B, Q_C, Q_D and Q_E are positive free terms, and f_A, f_B, f_C, f_D and f_E are functions of nonbasis unknowns.

These expressions are the solution to the system of equations (7) satisfying the conditions laid down when the equations were formed.

If the free term is negative in any of the equations for the basis product, this means that this basis product is incompatible with the other chosen basis products for satisfying the specified conditions. In that case we must change one of the basis products (any one) and derive the formulas again. The product which previously was a basis product will now appear in the new formulas as a nonbasis product. /378

The equations (11) can be used to select from available food products a diet of specified calorific value and with specified relative proportions of proteins, fats and carbohydrates.

A specified diet can be selected either from basis products only or from basis and nonbasis products.

TABLE 1. List of Products and Their Chemical Composition

Product	Chemical Composition, %						
	C	VF	AF	VP	AP	Water	Other (Ash, Cellulose)
A ₁ — Sweet Potato	23.5	—	—	2.0	—	72.0	2.5
A ₂ — Potato	21.0	—	—	2.0	—	75.0	2.0
A ₃ — Cabbage	5.4	—	—	1.8	—	90.0	2.8
A ₄ — Beetroot	10.8	—	—	1.3	—	86.0	1.9
A ₅ — Carrot	8.0	—	—	1.5	—	88.5	2.0
A ₆ — Onion	9.6	—	—	3.0	—	86.0	1.4
A ₇ — Lettuce	2.2	—	—	1.5	—	95.0	1.3
A ₈ — Dill	7.5	—	—	2.5	—	84.7	5.3
A ₉ — Parsley	11.0	—	—	1.5	—	85.0	2.5
A ₁₀ — Peanut	15.5	44.5	—	27.5	—	7.5	5.0
A ₁₁ — Chlorella	7.0	3.0	—	15.0	—	70.0	5.0
A ₁₂ — Beef	—	—	11.0	—	81.0	4.0	4.0
A ₁₃ — Cream Cheese	6.0	—	50.0	—	33.0	4.0	7.0
A ₁₄ — Cream	30.1	—	43.2	—	20.0	2.7	4.0
A ₁₅ — Chocolate	53.2	37.2	—	6.3	—	1.0	2.3
A ₁₆ — Powdered Egg	1.8	—	99.5	—	44.0	8.5	3.5
A ₁₇ — Cows' Butter	—	—	—	—	—	0.5	—
A ₁₈ — Almonds	10.0	55.0	—	21.0	—	8.0	6.0
A ₁₉ — Vegetable Oil	—	99.9	—	—	—	0.1	—
A ₂₀ — Buckwheat	73.8	1.8	—	8.5	—	14.0	1.9
A ₂₁ — Rice	75.8	1.0	—	7.6	—	14.0	1.6
A ₂₂ — Sugar	99.9	—	—	—	—	0.1	—
A ₂₃ — Wheat Flour	72.9	1.1	—	11.0	—	14.0	1.0

In the first case, in Eqs. (11) we must represent all nonbasis products as equal to zero, in which case the basis products taken in amounts determined by the free terms will constitute the specified ration. If it is desired to include in the diet one (or several) nonbasis products in addition to the basis products, we must specify the quantity of nonbasis product (or products) needed and substitute this value (or these values) in Eqs. (11). Solution to Eqs. (11) will then show us the quantities of basis products we must take in order to secure the specified diet, making allowance for the nonbasis products taken in addition.

The quantity of any nonbasis product which may be taken can only be that which, if substituted into Eqs. (11), does not give a negative solution in any of the equations.

To explain the technique of calculating a required diet more clearly and to demonstrate its possibilities, let us solve several concrete examples.

EXAMPLE

Problem. Compile a diet with a total calorific value of 2700 kcal and with the ratio $P : F : C = 1.25 : 1 : 4.72$.

Of the total protein content, $VP = 40\%$ and $AP = 60\%$, and of the total fat content $AF = 80\%$ and $VF = 20\%$.

To form this diet, the products listed in Table 1, items 1 to 19 inclusive, are to be used.

Solution. By means of Eqs. (3) we determine the quantity of proteins, fats and carbohydrates needed to satisfy the specified calorific value: $P = 100$ g, $F = 80$ g, $C = 377$ g.

By calculating the proportions we obtain the quantities of VP , AP , VF and AF : $VP = 40$ g, $AP = 60$ g, $VF = 16$ g, $AF = 64$ g.

We have thus found that to satisfy the specified calorific value and the specified proportions of proteins, fats, and carbohydrates, we must have: carbohydrates (a) = 377 g; vegetable fats (b) = 16 g; animal fats (c) = 64 g; vegetable proteins (d) = 40 g; animal proteins (e) = 60 g.

Using the data in Table 2 and Eqs. (8), we form the null-equations of the system (it will be noted that in Table 2, for convenience, the products are denoted by the one letter A with the index number of the product).

When solving problems such as this, it is desirable to list the specified products in a table similar to Table 1, for this greatly facilitates the formation of the null-equation, because all coefficients of each null-equation are then found in one column only. For example, for the null-equation of carbohydrates [Eq. (1) of system (8)] they are in Column C, for the null-equation of vegetable fats [Eq. (2) of the system (8)] they are in column FV, and so on.

The null-equations of our example include 19 specified products.

$$\begin{aligned}
1. \quad 0 &= 37700 - (23.5 A_1 + 21 A_2 + 5.4 A_3 + 10.8 A_4 + \\
&+ 8 A_5 + 9.6 A_6 + 2.2 A_7 + 7.5 A_8 + 11 A_9 + 15.5 A_{10} + \\
&+ 7 A_{11} + 6 A_{13} + 30.1 A_{14} + 53.2 A_{15} + 1.8 A_{16} + 10 A_{18}); \\
2. \quad 0 &= 1600 - (44.5 A_{10} + 3 A_{11} + 37.2 A_{15} + \\
&+ 55 A_{16} + 99.9 A_{19}) \\
3. \quad 0 &= 6400 - (11 A_{13} + 50 A_{15} + 43.2 A_{14} + \\
&+ 42.2 A_{16} + 99.5 A_{17}) \\
4. \quad 0 &= 4000 - (2 A_1 + 2 A_2 + 1.8 A_3 + 1.3 A_4 + 1.5 A_5 + \\
&+ 3 A_6 + 1.5 A_7 + 2.5 A_8 + 1.5 A_9 + 27.5 A_{10} + 15 A_{11} + \\
&+ 6.3 A_{15} + 21 A_{18}) \\
5. \quad 0 &= 6000 - (81 A_{12} + 33 A_{13} + 20 A_{14} + 44 A_{16})
\end{aligned}
\tag{12}$$

Let us choose as our basis products: A_1 (sweet potato), A_{11} (Chlorella), A_{12} (beef), A_{15} (chocolate) and A_{17} (cows' butter). /380

Using the order of solution of the system of equations given above for seeking nonnegative solutions, we obtain working formulas corresponding to Eqs. (11) for our chosen basis products A_1 , A_{11} , A_{12} , A_{15} and A_{17} , by means of which we can draw up the specified diet composed of the necessary products.

$$\begin{aligned}
A_1 &= 1501.7 - (0.89228 A_2 + 0.21915 A_3 + 0.45691 A_4 + \\
&+ 0.33335 A_5 + 0.3904 A_6 + 0.08314 A_7 + 0.30145 A_8 + 0.4645 A_9 + \\
&- 2.241 A_{10} + 0.2591 A_{13} + 1.3008 A_{14} + 0.07796 A_{16} - \\
&- 3.0705 A_{18} - 6.06 A_{19}); \\
A_{11} &= 50 - (0.014847 A_2 + 0.093932 A_3 + 0.026664 A_4 + \\
&+ 0.05757 A_5 + 0.15322 A_6 + 0.092115 A_7 + 0.1515 A_8 + \\
&+ 0.039392 A_9 + 1.685 A_{10} - 0.035754 A_{13} - 0.179785 A_{14} - \\
&- 0.010794 A_{16} + 1.2302 A_{18} - 0.335 A_{19}); \\
A_{12} &= 74.1 - (0.407 A_{13} + 0.247 A_{14} + 0.544 A_{16}); \\
A_{15} &= 39 - (-0.001195 A_2 - 0.00757 A_3 - 0.00215 A_4 - \\
&- 0.00464 A_5 - 0.01235 A_6 - 0.00744 A_7 - 0.0122 A_8 - \\
&- 0.00318 A_9 + 1.059 A_{10} + 0.00288 A_{13} + 0.0145 A_{14} + \\
&+ 0.000866 A_{16} + 1.38 A_{18} + 2.72 A_{19}); \\
A_{17} &= 56.1 - (0.458 A_{13} + 0.406 A_{14} + 0.364 A_{16}).
\end{aligned}$$

Let us now test the accuracy of the equations used for choosing the diets. /381

Let us assume that the diet must consist of basis products only. In that case, taking all nonbasis products equal to zero, by means of the working formulas we determine the necessary number of grams of basis products for the diet.

$$\begin{aligned}
A_1 &= 1501.7 \text{ g} \\
A_{11} &= 50 \text{ g} \\
A_{12} &= 74.1 \text{ g} \\
A_{15} &= 39 \text{ g} \\
A_{17} &= 56.1 \text{ g}
\end{aligned}$$

Knowing the percentage content of all components of each product (Table 1), we can determine the content of each component in grams in the whole diet and compare the result with that given. These calculations are shown in Table 2, and it is clear that the chosen diet fully satisfies all the specified requirements.

TABLE 2. Results of Calculation for Basis Products

Product	Weight of Product, g	C, g	VF, g	AF, g	VP, g	AP, g
A ₁ — Sweet Potato . . .	1501,7	352,75	—	—	30	—
A ₁₁ — Chlorella	50,0	3,5	1,5	—	7,5	—
A ₁₂ — Beef	74,1	—	—	8,15	—	60
A ₁₅ — Chocolate	39,0	20,75	14,5	—	2,5	—
A ₁₇ — Cows' Butter . . .	56,1	—	—	55,85	—	—
Total	—	377	16	64	40	60
Specified		377	16	64	40	60

Total Calorific Value 2700 kcal

Commas represent decimal points.

Let us now assume that, besides basis products, the diet must include one nonbasis product, namely, onion in an amount of 50 g, i. e., $A_6 = 50$ g. Then, making all nonbasis products equal to zero except for $A_6 = 50$ g, by the working formulas we have:

$$\begin{aligned}
A_1 &= 1501.7 - 0.3904 \cdot 50 = 1482.2 \text{ g}, \\
A_{11} &= 50 - 0.15322 \cdot 50 = 42.3 \text{ g}, \\
A_{12} &= 74.1 \text{ g}, \\
A_{15} &= 39 + 0.01235 \cdot 50 = 39.6 \text{ g}, \\
A_{17} &= 56.1 \text{ g}.
\end{aligned}$$

All the checking calculations for this diet are given in Table 3, which shows that this diet also completely satisfies the specified demands.

This example is given to assist in explaining the method of calculation and to show how it can be used, in principle, to choose a diet of specified calorific

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value and with specified proportions of proteins, fats and carbohydrates from a limited assortment of products.

TABLE 3. Results of Calculation for Basis Products and One Nonbasis Product (Onion)

Product	Weight of Product, g	C, g	VF, g	AF, g	VP, g	AP, g
A ₀ — Onion	50	4,8	—	—	1,5	—
A ₁ — Sweet Potato . . .	1482,2	348,2	—	—	29,7	—
A ₁₁ — Chlorella	42,32	3,0	1,27	—	6,35	—
A ₁₂ — Beef	74,1	—	—	8,15	—	60
A ₁₅ — Chocolate	39,617	21,0	14,73	—	2,45	—
A ₁₇ — Cows' Butter . . .	56,1	—	—	55,85	—	—
Total		377	16	64	40	60
Specified		377	16	64	40	60

Total Calorific Value 2700 kcal

Commas represent decimal points.

The specialist must determine precisely which products and how much of each product must be taken from a given assortment, on the basis of the formulas obtained in order to adhere approximately (or perhaps exactly) to the intended menu.

It will be clear from the examples given above that, being in possession of working formulas, it is possible to determine the proportions in which necessary products from a limited assortment must be taken in order to ensure that the diet for selected menus conforms to the specified calorific value and specified content of proteins, fats and carbohydrates.

HETEROTROPHIC ORGANISMS AS A SOURCE FOR HUMAN CONSUMPTION DURING LONG SPACEFLIGHTS

V. I. Yazdovskiy and G. S. Ratner

Many Soviet and Western investigators are becoming convinced that the possibility of making long space flights depends on the successful development of a life-support system based on the circulation of matter within a small confined space [2, 3, 7-11]. /383

Production of food on the basis of the circulation of matter not only dispenses with the need for large stocks of food products on board the spacecraft, which would itself limit the duration of man's stay in space, but also allows self-sufficiency for an indefinite period on the basis of the supply of chemical elements present on board the spacecraft at the time of launching, which includes the total sum of matter contained in the bodies of men and animals, in plants and in systems designed to maintain normal conditions for their vital activity during the spaceflight or during their stay on interplanetary stations and on planets. To this it can be added that including heterotrophic organisms in the life-supporting system based on the circulation of matter, it is possible to reduce the amount of energy irreversibly lost on account of negentropic processes observed in a biological system [4].

At the present state of our knowledge it would be unreal to consider that a miniature model of the terrestrial biosphere can be constructed on board the spacecraft, because the circulation of matter and energy on earth takes place with the participation of vast numbers of biological objects and of complex geochemical processes which have so far received little study.

The main aim of research workers attempting to introduce heterotrophic organisms as part of the general system of human life support during a stay in space has been to provide the crew with sufficient first-class protein and animal fat.

In the 24-hour period a man must receive approximately 104 g protein, 80 g fat and 447 g carbohydrates, and from 40-60% of the total protein taken must be protein of animal origin [10]. Hence, the first problem to be tackled is the selection of the most promising heterotrophic organisms from this standpoint and the investigation of their behavior in small closed spaces. Clearly the selected species of heterotrophs must not only provide first-class proteins and fats, but must also adapt themselves to life on limited areas and under conditions of a limited supply of oxygen, on a uniform and specific food basis (certain species of higher and lower autotrophs, human metabolic products). Another important factor is the psychological acceptability of particular species of heterotrophs as a raw material for food preparation.

From this point of view it is essential to examine representatives of the higher and lower heterotrophs.

The biomass of certain microorganisms, such as the lactic acid or propionic acid bacteria, and also certain other species, could in principle satisfy human requirements of animal protein. However, besides definite objections of a psychological character, the use of microorganisms as a human food product is largely prevented by the complexity of their cultivation. The slightest deviations from optimal parameters of the culture medium cause profound changes in their biochemical activity [6], so that this biological system is not reliable enough. It should also be mentioned that many microorganisms and, in particular, lactic acid bacteria most acceptable from the dietary point of view, require high-quality media for their growth (milk or a medium similar in chemical composition to milk), and from the economical point of view such media could conveniently be included directly in human food.

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Yeasts, being less fastidious, are more reliable and economically more suitable objects, but their use is restricted because they contain considerable quantities of purine and pyrimidine bases which are toxic to man.

The use of tissue cultures as a source of protein for human food is now of purely theoretical interest, being even more problematic than the use of a biomass of microorganisms. This is due partly to insufficient study of the problem as a whole, but also to the highly complex conditions of cultivation and the slow rate of growth of tissue cultures and the need for using media such as blood, embryos or multicomponent substrates containing a full range of amino acids and other valuable additives as media. It will thus be clear that the use of tissue cultures for food purposes would be completely unsuitable, not to mention the technical difficulties of cultivation.

A useful addition to the astronaut's diet would be some species of marine invertebrates, grown separately or in conjunction with fish. According to results obtained by various authors, mollusks and crustaceans are most interesting in this respect.

Mollusks (oysters, mussels) have long been used as human foods, and the calorific value of their meat is higher than that of fishes such as carp, cod and pike-perch. However, their use as components of a closed ecological system can hardly be justified, because they have a large shell and a long cycle of development.

Crustaceans are more promising as objects for study and use.

Artemia Salina L. (order Branchipoda), for instance, passes through a complete cycle of development in 6-22 days, it is resistant to contaminants in the water, and the adults use Chlorella and Scenedesmus as sources of food. The eggs of these crustaceans can withstand drying and freezing without detriment to their development.

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Crabs of the genus Daphnia (order Cladocera) possess many positive qualities: tolerance to lack of oxygen and contamination of the medium, considerable accommodation as regards food (they eat protococcal algae, bacteria, plant pollen). These crabs readily eat fish. However, to obtain 50 g protein daily, almost 50% of the human protein requirement, from Daphnia, with a productivity of 200 g/m^3 , the cultivation volume would have to be 31.3 m^3 water, and at the present stage this considerably restricts the possibility of their use.

Crabs of the genus *Gammarus* (order Amphipoda) are possibly more promising for study. *Gammarus* is omnivorous, feeding on decaying plant remains, debris, the bodies of dead marine animals, and other organic products. *Gammarus* will readily eat chicken [5]. An interesting species is *Gammarus locusta*, capable of existing and developing out of water. Calculations show that to obtain 50 g protein daily by the use of *G. locusta*, an area of 8.2 m² is sufficient.

Another possible source of human food during long space flights is fish.

Fish meat is not inferior to beef in food value and assimilability, and it contains first-class proteins and readily assimilated fats. Fish meat has a high content of phosphorus compounds (up to 0.3% of the fresh weight), vitamins, especially vitamin B₁₂, which makes vegetable proteins more easily assimilated, mineral substances and trace elements, playing an important role in human nutrition.

However, only a few species of fish, which can adapt themselves to the specific conditions in which they are kept (restricted volume of water and oxygen, absence of variety of food), can live in small closed spaces. The fish must also breed readily and possess a rapid rate of growth. Species of fish possessing these properties to a varying degree include the white amur, silver carp, common carp and tilapia. The mean daily increase in weight of these fish is 1.3-4.8 g, their oxygen consumption 0.1-1.4 mg/h/g body weight, optimal temperature 23-27°, and optimal pH 6-8.

The species of the genus *Tilapia* which has received most study is *Tilapia mossambica* (Peters). This species is highly accommodating in its requirements and can live in tanks with very low oxygen concentration and in water with a wide range of pH values (from 4 to 10). The tilapia becomes sexually mature in 3-4 months and by the age of 10 months may achieve a weight of 850 g. Adults are omnivorous and eat both plankton organisms and plants. An experiment has also been carried out in which solid waste products of human metabolism were used as food for tilapia [12].

From the point of view of the possibility of storing the eggs for a long time and then reproducing the stock later, the spawning cyprinidonts are worthy of attention because their eggs can be stored in a dried state for considerable periods. /386

On the assumption that the whole of the essential animal protein required to meet a man's daily needs (50 g) must be obtained entirely from fish meat, the fresh weight of meat required would be 396 g (calculation for *T. mossambica*). To obtain this amount of meat, four fishes aged five months, each weighing 180 g, would be required every day. To use this number of fish daily, it would be necessary to have five age groups, with 120 fish in each, and, in addition, to have six adults (4 females and 2 males) for breeding. The total weight of these fish would be 51.6 kg. With a stocking density of 15 g fish per liter, in order to keep this number of fish 3440 liters water would be required, and the whole population would utilize about 112 liters oxygen daily.

It thus follows that the most vulnerable aspect of tilapia as a possible component of the life-support system for small closed spaces is the fairly considerable

weight (about 3.5 tons) of medium where it can live. However, there is reason to suppose that the stocking density of fish per unit volume of water and their rate of growth may both be increased, and if it is remembered that only part of the astronaut's daily requirement of animal protein will be met by fish meat, the weight and volume of the tank for the fish may be substantially reduced. Certain species can thus be recommended for breeding on board the spacecraft for long flights.

The domestic hen is also of considerable interest as a source of first-class protein and animal fat. The attractiveness of the hen as a heterotroph for growth on board the spacecraft is connected with its rapid rate of growth, ease of reproduction and, more especially, with the possibility of obtaining food products of first-class quality from the nutritional and psychological aspects.

On the basis of data reported by a group of workers [1], it may be calculated that to obtain 50 g protein in the form of chicken and eggs, a constant number of 44-46 adult and young birds must be kept. Such a flock would consume about 1360 liters oxygen daily.

It is particularly worth mentioning that the amount of nutritive substances which a hen must receive (approximately 165 kcal/kg body weight) can be provided to a large extent by feeding with offal (30 kg bird offal daily), marine invertebrates (up to 50 g), leaves of higher plants (80 g beetroot leaves daily), and solid waste products of human metabolism.

It may thus be postulated that if birds (hens) are included in the life-support system, the problem of obtaining first-class food products can be solved most economically because of maximal utilization of residues and waste products. It must be remembered, of course, that to keep the required number of birds, a large quantity of oxygen (up to 1360 liters) per day must be provided. /387

So far, we have discussed mainly the species of heterotrophic organisms which can be used directly as human food, and which are, consequently, of the greatest interest as objects for keeping on the spacecraft or interplanetary orbital stations. Unfortunately, both birds and fishes, and also some species of marine invertebrates, in turn require a certain amount of first-class animal protein. For hens, for example, the daily requirement of digestible animal protein is about 20 g/kg body weight. Moreover, it may happen that the higher heterotrophs and marine invertebrates used directly as human food cannot fully utilize human metabolic products and the whole biomass of algae and leaves of higher plants used as oxygen producers. The need arises for including among the heterotrophs what are known as primary utilizers of organic matter.

For this purpose we have examined a series of lower heterotrophic organisms. However, even members of the lower heterotrophs such as the earthworm Enchytraeus albidus Henle, the midge Chironomus dorsalis Meig, the house fly Musca domestica L., the Asiatic locust Locusta migratoria, and certain others, despite definite advantages in their biological characteristics, cannot really be recommended for inclusion as heterotrophs because of difficulties of cultivation and the negligible economic gain from their use. Clearly, organisms forming active sludge are more promising in this respect. The active sludge used for biological purification of sewage consists of a stable bio-coenosis of various bacteria, protozoa, flagellates, and the larvae of worms and

insects. Active sludge contains up to 40% protein per dry weight and it is a source of first-class protein for higher heterotrophs. The diet of a bird may contain up to 5-10% of active sludge.

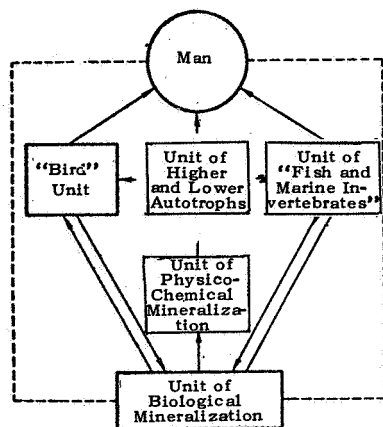


Diagram Showing Inclusion of Heterotrophic Organisms in the Human Diet System.

One of the possible variants of the food chain "man—heterotrophs" is shown in the figure. It should be remembered that the various species of animals shown in the diagram can be replaced by others (instead of birds, goats, pigs, etc., can be used), and certain units, such as the fish and marine invertebrate unit, may be completely left out of the life-support system if they are unnecessary.

In conclusion, some attempt should clearly be made to formulate certain general demands which the use of heterotrophs must satisfy. The heterotrophic organisms used must:

1. Reproduce food products of first-class quality, adequate in quantity and acceptable psychologically and with regard to taste;

2. Fit in well with the other units of the life-support system;

3. Be maximally reliable, i.e., allow certain deviations from optimal parameters, be resistant to the factors of space flight, and so on;

4. Be economical and, in particular, utilize most completely the remains of higher and lower

autotrophs, human metabolic products, and other waste products with a minimal loss of energy and oxygen.

The requirements listed above illustrate the great complexity of the problem of introducing heterotrophs as a source of human food for long spaceflights, a problem which must be solved within the very near future.

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WATER SUPPLY FOR THE CREW DURING SPACEFLIGHTS

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The provision of water for spacecraft crews is one of the more important systems of human life support. The design and construction of a water supply system for the crew in closed confined spaces are dependent in principle on the duration of the flight, the places where the inhabited objects are to function, the properties of cosmic space, and certain other factors. In short expeditions, the crew can best receive its water supply from reserves of drinking water. In this case the normal levels of water consumption are of great importance. However, there are no single normal standards for water consumption by man. According to data in the literature, the volume of drinking water required by a man per day ranges from 1600-2200 ml [11, 12, 13, 18, 20, 22].

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A system of water supply based on the use of reserves necessitates the development of ways and means of storing and disinfecting of water. The most effective preservatives of drinking water are coumasin and ionic silver.

In flights lasting several weeks, the need arises for creating an artificial water circulation based on physico-chemical or biological processes.

During the last few years a number of physico-chemical methods have been suggested for regenerating water from human and animal metabolic waste products to supply the crew of spacecraft: distillation under atmospheric pressure, vacuum distillation, extraction, vacuum distillation combined with high-temperature pyrolysis of volatile compounds, a catalytic method under atmospheric and reduced pressures, lyophilization, a method using semipermeable membranes, and so on. Making allowance for the specific conditions on board the spacecraft, and the degree of perfection of water regeneration methods, it seems that the methods of vacuum distillation, lyophilization, the catalytic method, or combinations of these may be capable of practical application.

By means of vacuum distillation at 3 mm Hg and 6-7°, water was obtained which, after additional purification with activated charcoal, satisfied hygienic standards [11].

Welch and co-workers [21] designed a vacuum distillation apparatus which was used in a simulated spacecraft cabin. Two subjects consumed water obtained from human metabolic waste products at a reduced pressure and temperature of 35-37° for a period of 30 days. The water was purified additionally by activated charcoal filters.

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Investigations showed that the vacuum distillation method can be used without resort to raised temperatures, and since it utilizes the vacuum of cosmic space, this may prove to be a promising method of water regeneration. Disadvantages of this method include the need for an additional purification system based on filters of ion-exchange resins or activated charcoal, because the con-

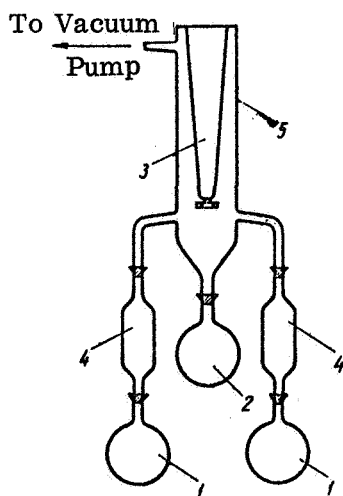


Figure 1. Diagram of Laboratory Apparatus for Water Regeneration by the Lyophilization Method. 1) Vaporizer-Sublimator; 2) Receiver of Regenerated Water; 3) Cryoscopic Mixture; 4) Trap; 5) Condenser-Refrigerator.

densate obtained by vacuum distillation is contaminated with volatile organic substances, ammonia and other compounds. Attempts were naturally made to devise a method free from this disadvantage. One such method is lyophilization. The process of lyophilization is usually carried out in a vacuum of the order of 10^{-3} mm Hg and at reduced evaporation temperatures (sublimation). By making use of differences in the volatilities and molecular weights of substances present in the original product, and the absence of decomposition or formation of new volatile compounds, it is possible to separate comparatively pure water from various food products [4]. However, when the lyophilization method was used to regenerate water from human metabolic waste products, a liquid with unpleasant taste and smell was obtained [19].

Regeneration of water by lyophilization without the need for additional purification was first successfully accomplished by means of a specially designed apparatus. A scheme of a laboratory apparatus for water regeneration from human metabolic waste products by the lyophilization method is shown in Fig. 1.

Water-containing human metabolic waste products are placed in the vaporizer (sublimator).

During evacuation of the regeneration system by the vacuum pump, intensive vaporization of the original liquid takes place, and this is accompanied by a sharp fall of temperature. If insufficient heat is supplied to the vaporizer, the solution for regeneration spontaneously freezes. Water vapor and some of the volatile compounds pass into the condenser-refrigerator, where freezing of the moisture and pollutants condensing under these conditions takes place. The uncondensed compounds are evacuated by the pump. Since violent frothing of the original solution is observed *in vacuo*, traps were used to prevent drops of solution from entering the condenser-refrigerator. After complete extraction of water from the solution, the system is filled with air to atmospheric pressure and the regenerated water formed during thawing of the ice enters the receiver.

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The laboratory apparatus described above was used to regenerate water from urine as one of the most highly contaminated sources of water and one of the most difficult to regenerate. Regeneration took place under a vacuum of

10^{-3} mm Hg, measured by a thermocouple vacuum gauge, and the temperature of the condenser-refrigerator was maintained at between -35 and -78° (a cryoscopic mixture of "dry ice" and alcohol). The vaporization temperature varied from -10° to $+2^{\circ}$. The results of tests of the lyophilization method for regenerating water from human urine are given in Table 1.

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This table gives a hygienic analysis of the water obtained without additional purification. Water regenerated from urine by lyophilization is a colorless,

transparent liquid with neither odor nor taste. As the table shows, the indices of quality of the water satisfy the demands made on drinking water. Toxicological investigations conducted on batches of rats showed that the regenerated water was perfectly fit for consumption. A characteristic feature of the water obtained is its extremely low content of salts and trace elements. If this water is to be consumed by man for long periods, it must be enriched by appropriate mineral components.

TABLE 1. Results of Hygienic Analysis of Water Regenerated From Human Urine by the Lyophilization Method

Indices of Quality	Magnitude of Index	Allowable Magnitude of Index
pH.	6,1—6,3	6,5—8
Transparency, cm	28—30	30
Color, deg.	0	20
Odor, points	1—2	2
Oxygen Demands, mg O ₂ /liter	3—5	2—6
Ammonia Nitrogen, mg/liter	2—3	1
Nitrite Nitrogen, mg/liter . .	0,003—0,06	0,01
Nitrate Nitrogen, mg/liter . .	0	2—40
Chlorides, mg/liter	7	200
Phosphates, mg/liter	0,02—0,3	0,1
Sulfates, mg/liter.	6—7	20—80
Hardness, mg-eq/liter	0	7
Urea, mg/liter	Traces	0
Uric Acid, mg/liter	0	0
Creatine, mg/liter	0	0
Bacteria Count, <u>Number of</u> Bacteria/ml	50—100	100

Commas represent decimal points.

With the lyophilization method as a basis, and utilizing the vacuum of cosmic space and the negative temperatures of the shaded side of the spacecraft, a water regeneration system involving minimal expenditure of energy can be created.

However, the lyophilization method has a number of disadvantages. First, the use of low temperatures for freezing water vapor requires orientation of the

spacecraft, and this is not always possible. Second, if a lyophilization system based on the use of the vacuum of cosmic space is created, allowance must be made for the inevitable loss of uncondensed molecules, for example, of nitrogen, oxygen, carbon dioxide and certain other compounds. In addition, some of the water is lost in proportion to the vapor pressure at the temperatures used.

A method which is free from these disadvantages is one based on the conversion of all volatile toxic strongly smelling and biologically active compounds of organic and inorganic origin into simple oxides or elements. Since these compounds consist mainly of nitrogen, hydrogen, carbon, oxygen and sulfur, their oxidation will produce water, carbon dioxide, and oxides of sulfur and nitrogen. By choosing appropriate conditions of oxidation, elementary nitrogen, water, carbon dioxide and oxides of sulfur can be obtained. The carbon dioxide is readily removed by absorbents in common use. The quantity of sulfur compounds in the volatile and gaseous constituents of the urine, condensate of atmospheric moisture and water used for domestic and hygienic purposes is small, so that the appearance of large concentrations of sulfur oxides in the regenerated water is improbable. Oxides of sulfur can be converted in water into sulfites or sulfates and are then easily removed by ion-exchange resins.

Volatile compounds of human metabolic waste products can be converted into oxides and elements by various physico-chemical methods: 1) thermal decomposition and oxidation at temperatures of 900-1000° or higher; 2) ozonization; 3) by an oxidative catalytic method; 4) by oxidation in a discharge; 5) by ultrasonic oxidation, and so on. /393

Thermal oxidation requires considerable energy expenditure and, consequently, it can be used only when corresponding supplies of energy are available on board the spacecraft.

Ozonization, which is widely used in the practical deodorization of drinking water [3], is of considerable potential value for regeneration of water from human metabolic waste products. The comparatively high energy expenditure required for ozone production may be provided by the ultraviolet component of the solar spectrum. Oxidation in a discharge and ultrasonic oxidation are still practically undeveloped. At the present time, therefore, the most realistic method of oxidation of volatile compounds is the catalytic method. The literature on complete catalytic oxidation of organic compounds contained in human metabolic waste products is scanty. We know, for example, that methane is oxidized on copper (200°), molybdenum (300°), silver (320°) and vanadium (480°) catalysts [1]. In the presence of the same catalysts, propane, butane and the higher homologs of the aliphatic hydrocarbons are oxidized. It has been shown [6] that acetic acid gives rise to carbon dioxide and water on magnesium-chromium and copper-chromium catalysts; methylethylketone, butyric aldehyde, and ether burn with the formation of a mixture of organic acids.

Extensive investigations have been carried out on the choice of catalysts for oxidation of carbon monoxide into carbon dioxide. Effective catalysts based on oxides of manganese, copper, silver and cobalt [5, 9] and chromite catalysts—oxidizing agents based on silver permanganate [2] have been discovered.

However, the conditions under which oxidative catalysts must work in a water regeneration system are far different from those usually adopted. For example, many catalysts have their activity reduced when working in a humid atmosphere, but in a water regeneration apparatus the relative humidity will be in the region of 100%. Moreover, catalysts very often exhibit marked selectivity with respect to certain classes of compound. In the water regeneration system, however, the catalyst must effectively oxidize all volatile, strongly smelling, toxic and biologically active compounds.

Konikoff and Reynolds [15, 16] have developed a water regeneration system based on high-temperature oxidation of the volatile compounds of the urine. At 800-1000°, in a reaction zone fitted with a platinum grid under a vacuum of 60 mm Hg, all volatile compounds were destroyed, thus producing water fit for consumption. These workers performed an experiment using human subjects. For six days the subjects drank water regenerated from the urine by the method just described. No effects on the subject were found.

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This method is difficult to apply under the actual conditions of space flight, because temperatures of 800-1000° C are difficult to attain (at least during forthcoming flights of short duration).

The present authors have developed a catalytic method of water regeneration from all moisture-containing human metabolic waste products using oxide catalysts. Catalysts prepared on the basis of oxides of certain elements have been shown to work at much lower temperatures [8].

The regeneration system based on the use of oxidative catalytic processes can operate at either atmospheric or reduced pressures. A diagram of such an apparatus is given in Fig. 2.

Water-containing waste products of human and animal metabolism are placed in the receiver-vaporizer. During heating, water vapor and volatile organic compounds enter the catalytic furnace, where they are completely oxidized to nitrogen, water, carbon dioxide and oxides of sulfur. The temperature of the catalytic process is measured by a thermocouple. The vapor passes through the condenser-refrigerator, at a temperature of 10-18°, where it condenses and passes into the pure water receiver, while the uncondensed gases continue through the flow meter and blower. The atmospheric pressure is maintained by a pressure equalizer. The tap 8 is used for taking samples for gas analysis and tap 10 is used when water regeneration is to be carried out under reduced pressure.

The catalytic method was used to regenerate water from urine, condensate of atmospheric moisture, and water used for domestic and hygienic purposes. The relationship between the quality of the regenerated water and the temperature of catalytic oxidation, rate of circulation of air in the closed circuit, quantity of catalyst, nature of the catalytic oxidizing agent, and the geometric parameters of the catalytic reactor was investigated.

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Extensive tests were carried out on the regenerated water to determine its hygienic standard. The following methods were used: oxygen demand (perman-

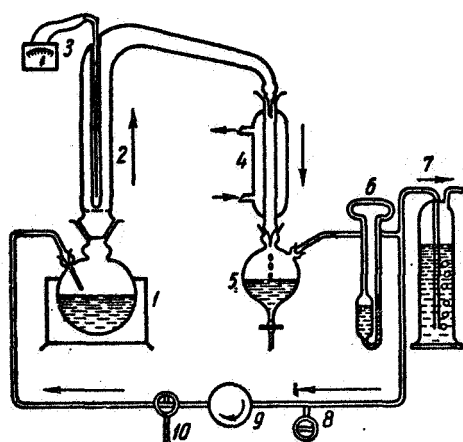


Figure 2. Scheme of Laboratory Apparatus for Water Regeneration by an Oxidative Catalytic Method. 1) Receiver-Vaporizer; 2) Catalytic Reactor; 3) Thermocouple; 4) Condenser-Refrigerator; 5) Receiver of Regenerated Water; 6) Flow Meter; 7) Pressure Equalizer; 8) 2-Way Tap; 9) Blower; 10) 3-Way Tap.

TABLE 2. Results of Hygienic Analysis of Water Obtained From Urine by the Catalytic Method

Tests	Indices of Quality of Regenerated Water	Allowable Indices of Water Quality
Oxygen Demand, mgO ₂ /liter	1,5	2-6
pH.	6,5-7	6,5-8
Transparency, cm.	30	30
Color, deg	15	20
Odor, Points.	0	2
Ammonia Nitrogen mg/liter.	0,1	1
Nitrate Nitrogen, mg/liter	0,1	40
Nitrite Nitrogen, mg/liter	0,02	0,01
Organic Nitrogen, mg/liter.	0	0
Sulfates, mg/liter	0-20	80
Chlorides, mg/liter.	0	200
Phosphates, mg/liter.	0,005	0,1
Hardness, mg-eq/liter.	0	7
Ca, mg-eq/liter	0	
Urea, mg/liter	0	0
Uric Acid, mg/liter.	0	0
Creatine, mg/liter.	0	0
Bacterial Count, No. of Bacteria, mg/l	0	100

ganate and bichromate methods), pH, transparency, color, odor, ammonia nitrogen (colorimetric method using Nessler's reagent), organic nitrogen (Kjeldahl method), nitrate nitrogen (colorimetric method using Griess's reagent), nitrite nitrogen (colorimetric method with disulfophenol indicator), sulfates (complexometric method using Trilon B indicator), chlorides (Mohr's method), phosphates (by Denny's cerulomolybdate method), hardness and calcium (complexometric method using Trilon B indicator), urea (Borodin's method), creatinine (Folin's method), uric acid, and also the number of colonies of *Escherichia coli* (bacterial count).

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The results of hygienic analysis of water obtained from urine by the catalytic method are given in Table 2. These results were obtained for water regenerated under the following conditions: temperature of catalyst 150°, rate of circulation 4-5 liters/min, temperature of condenser 18°, temperature of vaporization of original product 50°. The pressure of the vapor and air medium in the circulation system was atmospheric. Water regeneration took place on a catalyst prepared on the basis of manganese oxides.

Water obtained from human urine by the catalytic method is a colorless, transparent liquid with neither smell nor taste. The oxygen demand of the water (volume of oxygen required to oxidize organic contaminants), which is 1-5 mg O₂/liter, and also the absence of organic nitrogen, demonstrate that mineralization of the organic constituents of the urine is practically complete. As Table 2 shows, this water without further purification satisfies the hygiene standards of drinking water.

The quality of the water is highly dependent on the vaporization temperature of the original solution. Whereas the water obtained at a temperature of 50° fully satisfies the hygienic standards, at a temperature of 100° or above, slightly higher concentrations of ammonia and nitrites are observed, but these are readily absorbed by ion-exchange resins. The increase in ammonia concentration depending on vaporization temperature of the original solution may be attributed to an increase in the rate of decomposition of urea, hydrolysis of which is accompanied by the formation of ammonia and carbon dioxide. At 50° the degree of decomposition of urea is slight; if, however, water regeneration takes place at higher temperatures, the rate of urea decomposition rises, and most of the ammonium is set free after removal of a certain volume of water from the original solution. The quantity of ammonia in regenerated water as a function of the degree of extraction of water from the urine is shown in Fig. 3.

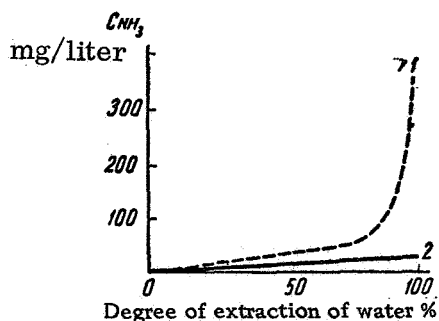


Figure 3. Changes in Ammonia Concentration in Distillate Depending on Degree of Extraction of Water From Urine. 1) Ammonia Concentration in Distillate with Catalytic Reactor not Working; 2) Ammonia Concentration with Reactor Working.

Curve 1 in Fig. 3 was obtained for a circulation apparatus when the vaporization temperature of the original product is 100°. In this case the catalyst in the reactor is uncharged. Curve 2 corresponds to the increase in ammonia depending on the degree of water extraction with the catalytic reactor working. It is clear from Fig. 3 that up to 80-90% of water extraction, the distillate contains a negligible quantity of ammonia, but thereafter a sharp increase is observed in its concentration. The sharp rise in ammonia is evidently due to an increase in the rate of decomposition of urea by the action of catalytic salts, whose catalytic action begins to be exhibited distinctly only at high concentrations of solid residue of the urine.

The quality of the regenerated water and productivity of the apparatus are influenced by the barometric pressure in the circulation system. A reduced pressure of 360 mm Hg created by a blower makes it possible to obtain drinking water for a long period, without the use of an additional purification system, with a considerably increased output of the regeneration system. A distinguishing feature of the work of the apparatus at reduced pressures is a sharp decrease in the formation of gaseous products.

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These investigations showed that catalytic system prepared on the basis of oxides of chromium, nickel and manganese may be used as catalytic oxidizing agents for water regeneration from human urine.

In the limited room available in the spacecraft cabin, a considerable proportion of waste products is accounted for by condensate of atmospheric moisture (1000-1200 ml/day per person) and by water used for domestic and hygienic purposes (1800-2000 ml). Regeneration of water from these sources is a task of no less complexity, despite the fact that the concentration of contaminants in the condensate and domestic water is much lower than in the urine. The difficulty in creating a reliable method of regenerating water from condensate of atmospheric moisture is the complexity and indefiniteness of its chemical composition. The condensate may contain secretions of the sweat and sebaceous glands, composed of fatty acids and their esters, proteins, urea and creatinine. The condensate is contaminated by volatile substances found in the urine and feces (amines, ammonia, mercaptans, hydrogen sulfide). Volatile components of covering materials, substances formed as a result of operation of equipment and instruments on board the spacecraft, and volatile compounds present in mixtures used for hygienic and disinfecting purposes make additional difficulties in the work of developing a method of water regeneration. Chemical analysis of the condensate obtained in one chamber showed that it contained the following contaminants: ketones, aldehydes, alcohols, amino-compounds, ammonia, and other compounds.

The chemical composition of the condensate as described above refers only to the particular conditions under which it was collected. If the environmental conditions in the spacecraft cabin are changed, the chemical composition of the condensate will naturally be different. Consequently, when developing a system of regenerating water from condensate of atmospheric moisture, the universality of the selected methods is important. From the energetic point of view, it is naturally convenient to regenerate water from condensate of atmospheric moisture by means of adsorbents and ion-exchange resins. However, it is an extremely difficult problem to create an adsorbent for a medium of indefinite and extremely varied chemical composition. The most acceptable solution to

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the problem of developing a system of water regeneration from the condensate of atmospheric moisture is the method of oxidation of all volatile organic compounds. For this purpose we have used the method of catalytic oxidation based on the design of the laboratory regeneration apparatus described above. The conditions for water regeneration from condensate of atmospheric moisture and water used for domestic and hygienic purposes were as follows: 1) temperature of catalytic furnace 150° , 2) temperature of condenser $15-18^{\circ}$, 3) air circulation rate 4-5 liters/h. The results of these investigations are summarized in Table 3.

TABLE 3. Chemical Composition of Water Obtained from Condensate of Atmospheric Moisture and Water Used for Hygienic and Domestic Purposes

Indices of Quality	Magnitude of Indices of Quality for Water Regenerated from		Allowable Indices for Drinking Water
	Condensate of Atmospheric Moisture	Hygienic and Domestic Water	
Oxygen Demand, mg O ₂ /liter.	1-2	1-3	2-6
pH.	6,5	6,5	6,5-8
Transparency, cm.	30	30	30
Color, deg.	10	10	20
Odor, Points.	0	0	2
Ammonia Nitrogen, mg/liter.	0	3,7	1
Nitrate Nitrogen, mg/liter ..	0,01	0,3	40
Nitrate Nitrogen, mg/liter ..	0,01	0,1	0,1
Organic Nitrogen, mg/liter..	0	0	0
Sulfates, mg/liter.	0	—	80
Chlorides, mg/liter.	0	—	200
Phosphates, mg/liter.	0	—	0,1
Hardness, mg-eq/liter.	0	0	7
Calcium, mg-eq/liter.	0	0	—
Urea, mg/liter.	0	0	0
Uric Acid, mg/liter.	0	0	0
Creatine, mg/liter.	0	0	0
Alcohols, mg/liter.	0	0	0
Aldehydes, mg/liter.	0	0	0

Commas represent decimal points.

Water obtained by the catalytic oxidation method from condensate of atmospheric moisture and hygienic and domestic water is a transparent liquid with no taste or smell. The indices of water quality satisfy the standards for drinking water.

However, it must be remembered that to give the regenerated water its customary taste qualities, hardness giving salts and trace elements must be added.

From repeated hygienic analyses of the regenerated water, it was concluded that it is suitable for drinking. This conclusion was confirmed experimentally in investigations of laboratory animals (rats). For three months the rats drank water regenerated from human urine.

These investigations showed that the regenerated water has no toxic action on rats.

Analysis of the results of combined hygienic, bacteriologic and toxicologic investigations indicated that experiments could safely be carried out on man.

The possibility of consuming water regenerated by the catalytic method was tested on three human subjects for 30 days. Clinical and physiological tests were performed on the subjects before, during and after the experiment. The water metabolism, cardiovascular and respiratory systems, and hematologic and biochemical indices were investigated. As a result of these investigations it was concluded that water regenerated from urine by the catalytic method is fit for human consumption as drinking water. The human subjects taking part in the experiment showed no pathological changes or manifestations of toxicoses.

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POSSIBLE USE OF WATER CONDENSED FROM A VIABLE CABIN
ATMOSPHERE FOR DRINKING AND OTHER
DIETARY PURPOSES

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N. A. Gaydamakin

One of the simplest ways of regenerating water during space flights is the use of a condensate of water vapor obtained from the cabin air by physical drying [4, 5].

The atmosphere of living rooms is contaminated by a number of volatile substances, the source of which may be man himself or the materials used in the construction and partitioning of the cabin, in electrical insulation, and other purposes. Most of these substances pass into the condensate when water vapor is condensed, making it unsuitable for direct use as drinking water.

In this paper we describe the results of a preliminary toxicologic investigation of condensate of atmospheric vapor from a hermetically closed cabin obtained while a person stayed in it for several days, and of an investigation of the effectiveness of its purification by means of ion-exchange resins and activated charcoals (KU-2, EDE-10p, AV-27, BAU, and so on). Suitability of water obtained from the condensate for drinking purposes was investigated in a long-term experiment on young rats, after which the regenerated water was used in a human diet.

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The material subjected to toxicologic investigation was a condensate obtained during an experiment, which lasted for several days, in a pressure chamber using human subjects, the air being regenerated by a supply of fresh oxygen and by means of a chemical lime absorbent. The chemical composition and hygienic properties of the condensate and the water obtained from it are given in Table 1. Examination of the data given in Table 1 shows that the condensate contained large quantities of ethyl alcohol, due to the fact that the subjects used toilet articles containing ethanol. Since this is poorly absorbed by ion-exchange resins and charcoals, nearly all the alcohol contained in these toilet preparations found its way into the regenerated water.

In the course of the experiment the concentration of ethyl alcohol in the condensate varied within wide limits (up to 3-4 g/liter) depending on the intensity of its entry into the cabin atmosphere. The oxygen demand of the condensate, which was mainly determined by its ethanol concentration, varied within equally wide limits. Accordingly, a series of experiments with 0.5% ethanol solution was included in the toxicologic investigation.

To obtain preliminary toxicologic data for the condensate, frog (*Rana temporaria*) embryos at the late blastula stage [1] were used. The embryos were kept in batches of 100 each in tap water (control), in purified and unpurified condensate, and also in 0.5% ethanol solution in tap water.

TABLE 1. Chemical Composition and Hygienic Properties
of Condensate Before and After Purification
by Absorbents

Indices of water and contaminants contained in it	Indices of water and amount of contaminants	
	Before purification	After purification
Odor, points	3—4	1
Color, deg.	—	3
Transparency (test type), cm.	20	> 30
Turbidity	Precipitated during storage	None
Taste.	Not detected	Traces of alcohol
pH	7.3	7.2
Cations, mg-eq/liter	2.25	0
Anions (fatty acids), mg-eq/liter	2.5	0
Ethyl alcohol, mg/liter.	~ 300	294
Oxygen demand, bichromate, mg O ₂ /liter	237	204
Including that due to Ethanol	—	196
Other contaminants		8
Oxygen demand, permanganate, mg O ₂ /liter	70	40
Nitrogen (Kjeldahl), mg/liter	70	0
Ammonia, mg/liter	75	0—0.3
Hydrogen sulfide and mercaptans, mg/liter.	1.5	0
Formaldehyde, mg/liter	Traces	0
Acetaldehyde and other aldehydes, mg/liter.	20	0
Amines and amino acids, mg/liter	Traces	0
Ketones, mg/liter	20	0
Calcium, mg/liter	16	0
Magnesium, mg/liter	7	0
Nitrite nitrogen, mg/liter	0.4	0
Nitrate nitrogen, mg/liter	0.1	0
Chlorides, mg/liter	Traces	0
Sulfates, mg/liter	Traces	0
Copper, mg/liter.	3.25	0
Iron, mg/liter.	Traces	0
Coli titer	Over 500	Over 500
Total bacterial count	No growth	No growth

The embryos developed identically in the purified condensate, in water containing ethanol, and in the control series, and by the 5th day of the experiment they had changed into free-swimming larvae. Their subsequent development, which was examined for the next 10 days, showed no difference between the control and experimental batches. Development of the embryos kept in unpurified condensate ended at the end of the first or beginning of the second day of the experiment at the late gastrula or neurula stage, and later all the embryos died.

One of the causes of this high toxicity of the condensate could be ions of copper and, perhaps, of other metals, for condensation of the water vapor took place on a metal surface. To test this hypothesis, an additional experiment was carried out using unpurified condensate in which all cations were replaced by sodium ions by means of the cation-exchange resin KU-2. /402

In these experiments 90% of the embryos died at the same stage as in the series with unpurified condensate, 5% of the embryos showed retardation in size and developmental defects of the caudal region at the moment of emergence from the membranes, and only 5% of the embryos completed their development without visible disturbances and shed the egg membranes at the same time as the controls. /403

These results show that the well-marked toxic effect of the unpurified condensate is not due to contamination with copper or other ions so much as to the other substances contained in the condensate. At the same time, the results demonstrate the great effectiveness of the methods used to purify condensate. Ethyl alcohol had no significant effect on development of the embryos, whether acting alone (in 0.5% solution) or in possible combination with unidentified contaminants in the purified condensate.

In the next experiments to study the effect of drinking regenerated water, male albino rats initially weighing 170-180 g were used. The experimental animals were divided into four groups, with 15 rats in each. The animals of Group 1 received purified condensate, with the hygienic properties indicated in Table 1, to drink. The animals of Group 2 received the same condensate with the addition of mineral salts to correspond to their content in Moscow tap water, those of Group 3 received tap water with the addition of 0.5% ethyl alcohol, and the rats of Group 4 received plain tap water (controls). The experiment continued for 105 days.

The state of the animals was judged from their behavior, the quantity of water and food consumed, changes in body weight, and the hemoglobin concentration and erythrocyte and leukocyte counts in the peripheral blood.

During the experiment the total volume of water drunk by the animals of the control group was 30 liters. The animals of the experimental groups drank 26 liters of purified condensate, 20 liters of condensate with the addition of mineral salts, and 18 liters of water with the addition of alcohol. Comparison of these results demonstrates the selective reticence of the experimental animals to drink water containing alcohol and also condensate with corrected salt composition.

The general condition of the experimental animals, their behavior and food consumption, and the dynamics of their body weight throughout the experimental

period were indistinguishable from those in the animals of the control group. The changes in blood morphology in the animals of the control and experimental groups were within normal physiological limits and no differences were found between the groups.

At the end of the experiment 40 rats were autopsied. The animals were killed with ether vapor. The relative weights of the adrenals, thymus and spleen were determined at autopsy. Macroscopic investigations were made of the mucous membranes of the pharynx, larynx, trachea, gastro-intestinal tract and urinary bladder. Observations were made on the state of the heart, lungs, liver, spleen, kidneys and adrenals.

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On five animals of each group microscopic investigations were made of the liver, kidneys, proximal and distal portions of the small intestine, brain, pituitary, thyroid, and adrenals. The organs taken for examination were fixed in 10% neutral formalin and stained with hematoxylin-eosin.

Analysis of the total body weight of the rats and the relative weights of the adrenals, thymus and spleen showed no statistically significant difference between the controls and experimental groups. The slight, nonspecific pathological changes found in the experimental animals were also observed in the control animals receiving tap water to drink. Because of the identical incidence of these changes in the control and experimental groups, they cannot be attributed to the quality of the fluid consumed.

The results of this experiment show on the whole that drinking condensate purified by absorbents or drinking tap water with the addition of 0.5% alcohol by animals for 3.5 months caused no pathological changes in the rats and was not reflected in their growth. It was therefore decided to test the use of purified condensate in human diet.

For the experiment on human subjects water was regenerated from condensate obtained from a hermetically closed model of a spacecraft cabin in which people were kept for several days. The air was regenerated by chemical methods. The system for collecting and purifying the condensate was constructed from neutral materials, and no ethyl alcohol was used in the cabin during the experiment.

The regenerated water used for drinking purposes had the following chemical composition and hygienic indices:

TABLE 2

Indices of Water	Result	Indices of Water	Result
Transparency, cm.	Over 30	Nitrogen (Kjeldahl), mg/liter .	0.84
Odor, points	1	Ammonia, mg/liter	0.3
Color.	Colorless	Ketones, mg/liter	0
Residue	Absent	Aldehydes, mg/liter	0
Taste.	Distilled Water	Indole, mg/liter.	0
pH.	6.8	Amines + Ammonia, mg/liter .	0.5
Cations, mg-eq/liter . . .	0	Hydrogen Sulfide and	
Anion, mg-eq/liter	0	Mercaptans, mg/liter	0
Oxygen Demand		Ethyl Alcohol, mg/liter. . . .	Traces
mg O ₂ /liter			
Permanganate Method . . .	3.6		
Bichromate Method	14.0		

During the experiment two subjects stayed in the closed cabin. The condensate of water vapor formed in the refrigeration unit was collected in a special receiver, passed through absorption columns, and its mineral composition was corrected by the addition of sodium, calcium and magnesium salts. /405

After analysis, the purified condensate was given to one of the subjects to drink directly or in the form of tea. The other subject drank only tap water.

During the six days of the experiment the first subject drank 6100 ml of regenerated water and the other drank 6550 ml of tap water. The subject drinking regenerated water observed no special differences in its taste or other properties.

In other experiments we repeatedly exchanged the tap water used for making tea on certain days for regenerated water, unknown to the subject. On subsequent interrogation, the subjects were never able to detect any difference between the tap water and regenerated water.

The results of physiological investigations during the experiment, together with the results of careful clinical examination of the subjects before and after the experiment, showed no change in the state of the first subject which could be attributed to drinking regenerated water.

The method of purifying condensate of water vapor from the living cabin by means of absorption, as used in these experiments, thus proved an effective means of obtaining drinking water under conditions simulating the spacecraft cabin.

The quality and potability of water used for drinking purposes under terrestrial conditions are governed by State Standards governing the choice of source of water supply and quality of water. In practice, under these conditions the potability of water is determined by the extent to which its characteristics satisfy the requirements of the State Standard for the composition of water and the hygienic state of the water source.

However, when determining the potability of water regenerated from human metabolic products (and, in the future, from metabolic products of other biological objects included in the ecological system), it would be incorrect to be governed entirely by the requirements of the existing health regulations for water supplies. These requirements, reflecting the natural origin of soil waters and the special nature of sources responsible for their pollution, cannot correspond fully to the provision of standards for the quality of artificially regenerated water. This is particularly true of the hygienic indices of water from springs.

In relation to regenerated water, when its composition is considered by itself, since the water is known to be of artificial (and not natural) origin, the modern physiological and hygienic principle of assessing the quality of drinking water from the standpoint of its effect on the living organism [3] becomes particularly important. On the basis of this principle, the hygienic standards governing the composition and quality of drinking water must be distinguished from its indices characterizing the hygienic state of the source of the water. The latter are particularly in need of correction as applied to the evaluation of regenerated water, because in this case the concept of water source is completely devoid of its original hydrogeological significances.

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As an example of these hygienic indices we may consider the oxygen demand. The requirements concerning oxygen demand restrict the allowable scale of contamination of the water source by products of natural bacterial decomposition of organic matter, a factor which is also associated with the possibility of bacterial contamination of the water. In the closed cycle of physico-chemical regeneration of water from water vapor condensate, sources of contamination of this character can be practically eliminated.

Meanwhile, under certain conditions alcohol may be present in the condensate, giving the water a high oxygen demand. The high oxygen demand of a water known to be contaminated with alcohol only cannot, of course, be considered in the traditional light as an index of the unsatisfactory hygienic state of the water supply. In this case the oxygen demand becomes essentially a criterion of the alcohol content, for which there is no hygienic standard in drinking water, although such a standard may be necessary in certain cases of water regeneration from condensate.

The situation may be the same also in connection with the content of nitrates and nitrites in water, for with certain methods of water regeneration (for example, from salt-containing nutrient media for plants) these cannot be regarded as indirect evidence of organic pollution. In this case the permissible concentration of these salts in the water must be revised, if it is to be used as a hygienic standard, from the standpoint of their effect on the human body.

These examples show that the existing requirements concerning the quality of drinking water must be supplemented by others allowing for the special fea-

tures of water circulation when it is regenerated in a closed system. Besides the usual demand that the permissible contaminants are harmless, it is also desirable to pay heed to the question of standardization of the concentration of "useful chemical ingredients" in water, a term introduced by P. Ye. Kalmykov [2]. Clearly, such a standard (for trace elements, for example) cannot be introduced without analysis of the movement of these ingredients along other, parallel channels of the circulation of matter.

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One of the problems in quality standardization of regenerated water is the establishment of supplementary standards and indices related to the special features of the water sources and the technology of its production. Because of differences between sources and technological methods of regeneration of water, these indices may likewise differ. For example, the indices of water quality differ if it is regenerated from metabolic products, from the decomposition of hydrogen peroxide, or from combustion of oxygen in fuel elements.

Because of this variety of sources and the inconstancy of composition of possible contaminants in the water when regenerated by different methods, the only reliable basis for determining potability of regenerated water is by direct investigation of its biological properties and its effects on the human body by consideration of each concrete method of regeneration.

One of the most general biological properties of water under terrestrial conditions is its property of being a life environment, and the evaluation of water with relation to this property must, in our opinion, be an essential element in the system of criteria used to determine the fitness of regenerated drinking water.

From the technical point of view this criterion can be easily determined by cultivating a series of animals and, perhaps, plants also in the water to be tested. The greatest difficulty here is that, of the tremendous number of possible zoological, botanical and microbiological objects, it is necessary to select the minimum which will suffice for enabling the biological suitability and harmlessness of the water to be established. Individual organisms and populations, as well as isolated organs can be used as such test objects.

A biological control of the quality of regenerated water along these lines may perhaps play an essential role during the development of different variants and stages of the technological process of water regeneration. In this connection, methods of biological testing of water quality in use at the present time are in need of additional study and extension from the standpoint of these new requirements.

We may conclude by saying that the approach to the standardization and quality of testing of regenerated water cannot be considered independently of the place occupied by the water regeneration system in the general system of circulation of matter. Our view on this aspect is that with the further development of life-support systems based on biological processes associated with different sources and with different ways of utilization of regenerated water, the question of establishment of hygienic standards for water must constitute only part of the general problem of its "ecological standardization."

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WAYS AND MEANS OF REDUCING TO A MINIMUM MICROFLORA IN
SMALL ROOMS INTENDED FOR LONG-TERM EXPERIMENTS
WITH SUBJECTS

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When organizing experiments in small rooms particular attention must be paid to measures designed to reduce to a minimum contamination of the room and articles in the subjects' environment by bacteria. /408

Under normal conditions of life the degree of bacterial contamination of dwellings, articles of everyday life and clothing is reduced by hygienic cleansing and also through the action of natural factors: ultraviolet radiation; ventilation; drying.

In rooms and other small spaces, the effect of external factors capable of destroying microorganisms is considerably restricted.

When subjects are required to stay for long periods in small rooms under hypodynamic conditions and in the absence of insolation, the general resistance of the human body is lowered and the natural bactericidal properties of the skin are reduced. Under these conditions an increase in the conditionally pathogenic microflora (staphylococci, streptococci, etc.) becomes a hazard.

The additional introduction of foreign microorganisms with various articles presented to the subjects in the room and during visits by the experimenters is undesirable.

Measures must therefore be taken to reduce to a minimum the number of microorganisms present at the beginning of the experiment and also to prevent the possibility of microorganisms entering during the experiment. /409

These measures are also necessary if a correct solution is to be found for problems in which a criterion is the dynamics of the bacterial population of the air, the surfaces of objects and clothing, and the subject's skin.

The following system of measures has been developed for reducing the degree of bacterial contamination of various objects.

Reduction of the bacterial population in the room (on the surfaces of the room: ceiling, walls, and floor; stationary equipment and apparatus).

During preparation of the small room for experiments, care must be taken to ensure that the ceiling, walls and floor of the room are faced with a smooth, nonporous material. The furniture must also be smooth and easily cleaned.

The foam-rubber mattresses, pillows, and chair seats must be covered with closely woven material.

The air-conditioning system must be fitted with a bacterial filter. The simplest method is to cover the air inlet with FPP-15 material.

The small room, the ante-room and the neighboring room for the experimenters on duty must be equipped with BUUV bactericidal ultraviolet lamps. The first two rooms should have lamps without reflectors and of a power of not less than 2W/m^3 . The lamps are controlled from the ante-room, but it is desirable that they can be switched on from the experimenters' room. The experimenters' room should be provided with ultraviolet lamps of combined action: NBO or PBO with a power of 1W/m^3 (calculated for the power of a lamp giving reflected radiation). By the use of such lamps, the rooms can be irradiated when people are present in them.

In one of the experiments, at our recommendation, a BUUV-15 bactericidal lamp was placed in the supply hatch. This should be done in every case if the supply hatch is large enough to accommodate such a lamp.

Before each experiment, the small room intended for this purpose, the ante-room and the experimenters' room should be treated in a special manner.

All unnecessary objects and furniture are removed, the surfaces of the room are thoroughly washed, and the furniture and windows in the experimenters' room are wiped over. The rooms are cleaned in the following order: 1) in the room intended for the subject (ceiling, walls and doors, then the floor); 2) ante-room (in the same order); 3) the experimenters' room.

For wet cleaning, a boiled scrubbing brush and water as hot as possible are used. The water and scrubbing brush are periodically replaced by fresh ones during the cleaning. At the end of cleaning, a mat for wiping the shoes is placed in front of the entrance to the experimenters' room. These rooms are then treated in the same order with 6% hydrogen peroxide, then thoroughly scrubbed with a sterile brush soaked in the same solution (twice), changing the solution and brush for fresh ones periodically. The volume of solution required is 300 ml m^2 for the ceiling and walls and 500 ml/m^2 for the floor. As a first step, under laboratory conditions, we demonstrated that this solution has no harmful effect on the various materials used. /410

After this scrubbing, the door into the small room and the supply hatch must be closed.

After an exposure of 1 hour, all the surfaces are wiped dry with a sterile brush.

The walls and floor of the ante-room and the experimenters' room, together with the furniture in them, are thoroughly scrubbed with 6% hydrogen peroxide.

At the end of this treatment of the rooms with the sterile brush soaked in a fresh 6% solution of hydrogen peroxide, the apparatus and equipment which can be treated in this manner are also scrubbed. After scrubbing, these objects are placed on a table in the ante-room and covered with sterile paper. The door of the ante-room is closed, and the UV lamps in it and in the subjects' room are switched on for not less than 2 hours.

At the end of this exposure the UV lamps are switched off. The laboratory assistant and experimenter put on sterile overalls, masks, neck cloths, cotton overshoes, and gloves, enter the ante-room along a sterile path, and place all the treated objects in the small room: beds, books, magazines, etc., and again switch on the UV lamps for the same exposure. At the end of this exposure the ventilating system is switched on long enough to give 14-16 changes of air in the subjects' room, after which they can be allowed to enter.

Treatment of soft objects. a) Bedding: mattresses, flock pillows, and blankets are freely packed in double-layered cloth bags and treated in disinfection rooms by a steam and air method under conditions ensuring death of spores: temperature 97-98°, load not exceeding 60 kg/m² useful area of room, exposure 30 min.

Along with the bedding, the paper bags into which the cotton bags with the bedding are placed at the end of exposure are also treated in the chamber. This method of packing prevents bacterial contamination of the treated objects during transportation and storage.

b) Overalls, masks, cotton overshoes, gloves, sheets, towels, pillow cases, /411 neck cloths, underwear, and gym shoes belonging to the subjects are sterilized by steam under pressure in an autoclave at 1.5 atm, temperature 126°C, exposure 30 min.

The masks, overalls and overshoes are packed together in sets. Each set is wrapped in two separate layers of paper. Sheets, pillow cases, towels and underwear for the subjects are arranged and packed in a similar way.

Besides these sets, a few sterile sheets, overalls and towels are packed individually for use if necessary. Gloves are packed in pairs, also in two layers of paper.

Books, writing materials, experimenters' notepads for introduction into the chamber, and the subjects' outer clothing, made of material not withstanding thermal disinfection, are irradiated with γ - rays in a dose of 2.5 MR, ensuring complete sterility. This was demonstrated by seeding the test object on nutrient media. The method of packing these articles was the same as described above.

Crockery and utensils for use by the subjects taking meals during the experiment: plates, spoons, forks, glasses are sterilized by dry heat at a temperature of 180° for 30 min or 165° for 2 hours.

If the subject obtained food from the food unit and it was poured into a dish given to the subject, this was done on a table covered with sterile paper, in sterile gloves.

If the food was given to the subjects after heating on an electric hotplate while actually in the dishes themselves, the outer surface of the dishes was thoroughly scrubbed with 6% hydrogen peroxide twice, replacing the brush for the second time, and only then were they placed in the supply hatch.

Order of washing adopted by subjects and of entry into the small room designed for the experiment. Just before the beginning of the experiment, arrangements were made for the subjects to have a hot shower, applying "Gigiyena" hexachlorophene soap or 2% chloramine solution over the whole of their bodies, after which they walked on sterile matting into the ante-room where they put on sterile underwear previously arranged in a definite order by the laboratory assistant. The laboratory assistant wears a sterile uniform (overall, overshoes, mask, gloves), places the objects on the bench, covered with a sterile sheet, and covers them with the edge of the same sterile sheet until the subjects come out from the shower.

After the subjects have put on their underwear, the experimenters, dressed in the same way as the laboratory assistant in sterile uniforms, take the necessary samples. They may also be wearing detectors at this time. The subjects then finish putting on their underwear and then put on their top clothes, and over them two overalls, mask, neck cloth, overshoes and gloves. If they need to go from one room into another, they put on an unsterile cloak, hat, and shoes over their other clothing. /412

The subjects take off the unsterile clothes and the top overall with the aid of the laboratory assistant when entering the experimenters' room.

Another laboratory assistant, also wearing a sterile uniform, meets the subject in the ante-room or just before entering the experimenters' room and helps him to remove the second sterile overall, overshoes, mask and gloves.

The subject walks along the sterile path made of matting or paper into the room. He puts on the sterile shoes which he must wear throughout the experiment at the entrance to the hatch.

If several subjects take part in an experiment, and they are all required to enter the small room designed for the experiment at the same time, each subject must be provided with the corresponding number of laboratory assistants, but it is more convenient for the subjects to enter one by one.

The experimenters, if entering the small room during the experiment, must put on sterile uniforms. At the same time, instruments and apparatus which they take in with them to the subjects must be treated. Disinfection of writing materials and paper has been dealt with previously. Any object taken in must be treated by the method described above.

Our observations show that the system of measures which we suggest is perfectly practicable and reduces the number of microorganisms in the subjects' environment.

After treatment in this way with 6% hydrogen peroxide, practically no microorganisms are found in the air and on the surfaces of the small room before

the beginning of the experiment, and the disinfecting itself has no harmful action on the materials of the rooms or on the subjects, in whom no complications were discovered during the experiments.

The level of bacterial contamination was much lower in experiments where these measures were carried out than in others where they were not used.

INVESTIGATION OF THE STATE OF THE HUMAN SKIN AFTER PROLONGED RESTRICTION ON WASHING

I. G. Popov, V. V. Borshchenko, F. K. Savinich, M. I. Kozar' and
A. M. Finogenov

For a long time manned space flights will evidently be undertaken under conditions of personal hygiene far removed from the normal terrestrial standards. The design and construction of special toilet facilities in compartments of spaceships present difficult problems. The supply of large quantities of water or other solvents and washing materials for the crew, the need to preserve or regenerate water used for washing and domestic purposes, frequent changes of underclothing, and so on, although relatively easily arranged under normal conditions become extremely difficult problems during space flight. On the other hand, our accepted concepts of the necessary scope and frequency of personal hygiene measures to which we are accustomed on the ground require adaptation to the very different hygienic conditions inside spacecraft. This applies above all to the quantity and quality of external contamination of the astronauts' skin, clothing and footwear. In small confined spaces, which initially were cleaned and disinfected, with practically no inflow of dust from outside, equipped with air-conditioning and ventilation units maintaining a stipulated gas composition and temperature of the atmosphere, the amount of external contamination of the astronauts' skin and clothing is reduced to a minimum. Very slight contamination may arise from dust formed from clothing, footwear, materials covering furniture and other equipment, and perhaps remnants of food, urine and feces not absorbed by the air-conditioning unit, and also bacterial aerosols.

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Another important and constantly acting source of contamination of the skin, clothing and environment is the astronauts' skin itself. Products excreted by the sweat and sebaceous glands, and also particles of desquamated epithelium and hair constitute an important, if not the main, source of contamination of the astronauts' skin and clothing. Quantitatively and qualitatively speaking this type of contamination, like that of the contamination not originating from the skin already mentioned, also possesses specific features under spacecraft conditions because of the special conditions for skin physiology: restriction of physical work and movement performed by astronauts, the unusual state of the autonomic nervous system and endocrine apparatus, the periodic nervous and mental strain, and so on. Yet another factor of importance is the rationing of food and water and the provision of rationally chosen conditions of temperature and humidity in the cabin, the wearing of specially designed clothing, the periodic wearing of pressure suits and other equipment, the negligible external contamination of the skin by substances capable of producing mechanical and chemical irritation of the skin, and the definite limitations as regards toilet of the skin.

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Because of the special hygienic conditions in spacecraft and of difficulties connected with toilet and washing of the skin and frequent changing of clothing, special measures had to be adopted for the hygienic treatment of the surface of

the body during space flight, and special uniforms had to be designed and regulations worked out for their use in order to provide satisfactory conditions in which the astronauts could live and carry out their activity.

To study contamination and the state of the skin and also of the astronauts' clothing materials, experiments lasting from 23 to 60 days were carried out. The subjects were men aged 19-26 years, clinically absolutely healthy, and during each experiment they remained continuously in closed rooms from 5 to 20 m³ in volume. Before the experiment the rooms were thoroughly cleaned and disinfected, using wet disinfectants and UFO bactericidal lamps. During the experiments the subjects' movements were restricted, and they spent most of the time sitting (during the day) or lying (at night and when resting during the day). The total physical exertion performed by the subjects daily, at a moderate rate, did not exceed 500 kg.m of work. The subjects received hot food three times in the course of the day, of varied and adequate composition. The mean energy value of the food (calculated) was 3000-3600 kcal/day. The water consumption was unlimited. In the experimental rooms automatic systems maintain the air temperature at 20-25° and the relative humidity at 40-60%, with air movement of about 0.1 m/sec. The rooms were fitted with push-pull ventilation. The clothing consisted of knitted underwear, a jersey, woven linen trousers of athletic type, cotton socks and light suede shoes. The microclimatic conditions and clothing were chosen to maintain the subjects comfortably warm and to reduce perspiration as much as possible during their period of limited movement. Imperceptible perspiration, of course, remained at the usual level for a normal barometric pressure and moderate atmospheric humidity.

A special feature of these experiments was prohibition of washing or other treatment of areas of the skin covered by clothing, i.e., about 80% of the total body surface. The skin of the face, hands and, in the case of some subjects, the feet was periodically cleaned with materials made up in water and alcohol. The underclothing, top clothing and socks were worn continuously for the 24 hours. The underclothing, top clothing and shoes were not changed to clean ones during the experiment. As a rule the socks were changed after 20-22 days, without any hygienic treatment of the skin of the feet. Earlier experiments showed that wearing the socks without changing them for longer periods is undesirable because of their considerable contamination by desquamated particles of the stratum corneum of the epidermis of the plantar surface of the feet. /415

The conditions created in these experiments to some extent simulated the hygienic situation in the spacecraft cabin. The skin and clothing of the subjects kept in isolation for long periods in clean small rooms became contaminated principally by human metabolic products: secretions of the sweat and sebaceous glands, desquamated epidermis and falling hair, and particles of feces and urine. Minor sources of contamination were food, dust from clothing, the floor and furniture, and the bacterial aerosol.

Contamination of the skin and clothing by products of the sweat and sebaceous glands was estimated from accumulation of chlorides and organic substances on them. Before and after the experiment, the washing water from all parts of the body surface covered by clothing was collected and the clothing was soaked in known volumes of tap water. Samples were taken from these aqueous extracts

TABLE 1. Accumulation of Chlorides (in mg chlorine) on Subjects' Skin and Clothing (mean data)

Duration of Experiment, days	Volume of Room, m ³	Number of Subjects	Total Accumulation of Chlorides in Clothing and on Skin, per day	Relative Content of Chlorides, %	
				On skin	In Clothing
23	20	3	242,8	9,8	90,2
30	7	6	208,7	9,4	90,6
30	5	2	260,3	20,2	79,6
60	7	4	231,1	3,4	96,6

Commas represent decimal points.

and the chloride content in them was determined by Mohr's method and the content of organic substances was estimated from their oxygen demand in mg O₂ by Kubel's method. Data for accumulation of chlorides and organic substances on the skin and clothing of the subject during the experiments are given in Tables 1 and 2.

TABLE 2. Accumulation of Organic Substances on Subjects' Skin and Clothing (from oxygen demand of aqueous extracts, in mg O₂; mean data)

Duration of Experiment, days	Volume of Room, m ³	Number of Subjects	Organic Substances in Clothing and on Skin (per day)	Relative Content Organic Substances, %	
				On Skin	In Clothing
23	20	3	796,8	14,3	85,7
30	7	6	567,0	12,1	87,9
30	5	2	411,5	17,3	82,7
60	7	4	480,1	6,7	93,3

Commas represent decimal points.

This comparison of mean data for accumulation of chlorides and organic substances on the skin and in the clothing shows that, despite the increase in total contamination of the skin and clothing by human metabolic products, the mean contamination occurring during the 24 hours, mainly by skin secretions, remained approximately stable during these conditions. Individual differences between subjects in development of contamination of skin and clothing were greater even though they were kept in identical condition as regards duration of the experiment and the microclimate. The combined contamination of skin and clothing per day by chlorides varied from 117 to 403 mg/day and by organic substances from 335 to 886 mg O₂/day.

The ability of the clothing to absorb large quantities of products of the sweat and sebaceous glands will be noted. In most cases the clothing absorbed about 90% of the chloride and 80% of the organic substances. The ability of clothing to remove large quantities of metabolic products from the skin was due both to the use of knitted materials highly permeable to moisture and lipids, and to the lightweight structure of the underwear, facilitating the passage of skin secretions into the clothing.

To assess the degree of contamination of the skin's surface by products of the sebaceous glands, the level of saturation of the layer of lipids on certain parts of the skin of the chest and back was determined. In the first seven days of the experiment the level of saturation of the lipid layer on these areas remained constant. Later the saturation level increased slightly because of accumulation of lipids presumably as a result of a decrease in the lipid-absorbing properties of the contaminated underwear materials. An experiment carried out under the conditions of normal life confirmed that underwear materials significantly affect the level of saturation of the lipid layer on the skin. The layer of sebum cutaneum on areas of skin covered by underclothing showed little change in its level of saturation after the second day of the experiment (about 100 $\mu\text{g}/\text{cm}^2$). On areas of skin isolated from contact with underclothing, the content of sebum cutaneum increased in the course of 5 days to 450 $\mu\text{g}/\text{cm}^2$. /417

The chemical composition of the lipids on the skin's surface underwent certain changes: the acid number increased on the average by 21% during the 30 days, while the saponification, ether, and iodine numbers decreased. The saponification number, for instance, fell on the average by 10% toward the 30th day. These changes in content of lipids constituting the secretion of the sebaceous glands of the skin are fully attributable to the action of atmospheric oxygen, moisture, components of the sweat, and also the action of enzymes secreted by microorganisms.

During the period of the experiment the pH of the skin surface shifted toward the acid side (5.12-5.68).

Bacterial contamination of the subjects' skin was investigated by O. G. Alekseyeva's agar impression method. The intensity of bacterial contamination varied from one part of the skin to another. During the first 2-3 weeks the number of microorganisms on most parts of the skin increased continuously, exceeding the initial background (freshly washed skin, 4-5 colonies/cm²) by 3-3.5 times. The level of bacterial contamination then became stabilized, with no tendency to rise

further. Meanwhile, more rapid growth of the microflora was observed on the skin of the plantar surface of the feet, the perineum and buttocks, exceeding the original figures at the end of the experiment by 7-12 times. After 30 days, the number of colonies per cm^2 was 68 on the buttocks and 82 on the foot. After 60 days there were 180-200 colonies per cm^2 on the arch of the foot. The change in pH of the mixture of substances on the skin surface towards the acid side during continuation of the experiment, together with the high cleansing power of the clothing materials, evidently restrained development of microorganisms and contributed toward stabilization of their growth. It is interesting that when underwear made of a mixture of synthetic materials and cotton was used, the level of bacterial contamination of the skin of the chest and back was somewhat lower than when cotton-viscose underclothing was worn.

The microflora on the skin surface and underwear consisted mainly of saprophytic species: Staphylococcus epidermidis, Staphylococcus albus, diphtheroids, and Sarcina.

The bactericidal power of the skin was determined with respect to Escherichia coli. Tests carried out on the skin in the region of the forearm showed a gradual decrease in bactericidal properties of the skin. The bactericidal index of the forearm skin was 90-95 before the experiment and 60-70 after 30 days.

Clinical observations on the state of the subjects' skin showed no significant changes in intensity of function of the sweat and sebaceous glands or in the state of the pilomotor and neurovascular apparatus of the skin. /418

Daily interrogation of the subjects disclosed moderate itching of the skin starting on the 2nd-3rd week of the experiment, in the region of the scalp, chest, back and feet. Later the intensity and frequency of itching of the skin increased. As a rule itching began after physical exertion and increased perspiration. The itching was relatively more marked in the region of the scalp, which received no hygienic treatment and was not cleansed by the clothing materials.

As the experiment continued, marked deposition of masses of keratin on the soles of the feet was observed. The relatively immobile mode of life followed by the subjects, particularly as regards walking, led to a sharp decrease in desquamation of keratotic scales on the soles of the feet, which under normal conditions is proportional to the load placed on the feet during walking. Meanwhile, the reproductive growth of the epidermis of the plantar surface of the feet continues, presumably at an intensity close to that under normal conditions of life, when the load on this part of the skin is considerable. It is interesting to note that in larger rooms with better opportunities for moving about, deposition of masses of keratin on the sole was much less, but contamination of the socks, on the other hand, increased.

Skin diseases discovered during the experiments are listed in Table 3.

The subjects developed skin diseases which are fairly widespread under normal conditions of life. The commonest disease encountered was folliculitis. This was localized mainly in the region of the buttocks and thighs, i. e., places of greatest and frequent pressure, friction, and moistening of the skin, because /419

TABLE 3. Skin Diseases Occurring in Persons under Restricted Skin Toilet Conditions

Duration of Experiment, days	Volume of room, m ³	Number of Subjects	Skin diseases (number of subjects)					
			Folliculitis	Furunculosis	Streptococcal In- tertrigo	Acne vulgaris	Dermatitis	Fungus diseases of the feet
23	20	3	1	—	—	—	1	1
30	7	6	5	—	—	1	—	—
30	5	3	3	2	1	1	—	1
60	7	4	3	1	—	2	2	—
Total	—	16	12	3	1	4	3	2

the subjects spent most of their time sitting in an armchair, even though the chair was soft. Subjects wearing headphones for several days to maintain continuous communication with the experimenters showed a high incidence of folliculitis on the skin of the face and neck. Folliculitis was much less common on the chest and forearms. Solitary furuncles which developed on three subjects were localized to the skin of the face, neck and forearm. They developed in the 2nd-3rd week of the experiment. In one case the furuncle was a complication of acne, and in the other of folliculitis. Acne vulgaris developed in subjects with a past history of hypersecretion of the sebaceous glands of the skin. In three subjects the acne was indurative in character, and in another it progressed to abscess formation. Dermatitis was observed at places of contact between the skin and pick-up electrodes of physiological and clinical apparatus. Streptococcal intertrigo developed in the perineal region in one subject. Contributory causes here were probably his flight obesity and increased tendency to perspiration. Epidermophytosis of the feet developed in one subject during the experiment. Another subject developed a squamous-dyshydrotic form of epidermophytosis of the feet before the experiment began. Under the influence of the relative rest and diminished moistening, the signs of epidermophytosis subsided in this case and by the 22nd day of the experiment examination of the skin of the feet revealed no pathological changes characteristic of epidermophytosis. The skin diseases did not appreciably interfere with the subjects' ability to work.

The skin diseases observed during the experiment could not be attributed entirely to the restricted hygienic and living conditions. Moreover, many cases of folliculitis, furunculosis and dermatitis developed on the face and exposed parts of the neck, which were cleansed with washing materials. Hygienic skin toilet would be more important for the region of the buttocks and thighs, where a more rapid growth of the microflora was observed. Even under ordinary conditions these diseases are common among people regular in their skin toilet habits.

Without denying the importance of special hygienic skin toilet for the prevention of such skin diseases in astronauts, at the same time, steps must be taken to raise the immunological and biological resistance of the body by rational feeding, work and rest. Improved furniture, the wearing of clothing of rational design and made from special materials and, in particular, the use of textiles with bacteriostatic and bactericidal properties, together with improved regulation of microclimatic parameters with a view to reducing perspiration during physical exertion and other situations of increased heat production, would have beneficial effects. /420

To summarize the results of these investigations it can be concluded that when the use of washing materials is limited under flight conditions, by choosing appropriate hygienic conditions in the spacecraft cabin (dust suppression in the cabins, rational design of toilet and domestic facilities, dietary systems, clothing, microclimate to correspond to heat production of the body, and so on), a considerable reduction in contamination of the astronauts' skin both by external contaminants and by products of skin metabolism can be obtained. Underwear with high cleansing properties occupies a particularly important place among these hygienic measures. Obviously under these conditions areas of skin not covered by clothing (the scalp, face, neck, and fingers) and also areas with increased contamination, such as the buttocks, the medial surface of the thighs, the plantar surface of the feet, and the interdigital clefts, must evidently receive hygienic treatment and cleansing under these conditions before the others.

Skin diseases arising after prolonged restriction of toilet facilities were those which are most commonly found and they had no appreciable detrimental effect on the general condition of the subjects and their ability to work. At the same time, the assortment of drugs kept on board the spacecraft must provide for the treatment of suppurative skin diseases which may arise.

ASTRONAUTS' BASIC REQUIREMENTS FOR PERSONAL HYGIENE MATERIALS

V. V. Levashov and A. M. Finogenov

Before scientifically based measures for hygienic care of human skin can be undertaken during long space flights, and before the study of the action of unusual conditions of life on board the spacecraft on the human body as a whole and on the skin in particular can be completed, all the basic physiological, biochemical, and microbiological constants of the human skin must be known. /420

Materials and methods of skin toilet must be effective both under the conditions of a changed gravitational field (allowing for changes in the behavior of fluids), and also when water consumption is limited.

Realizing the important positive role of the human symbiotic microflora, this factor must be taken into account when materials and methods of personal hygiene are devised and it must be correctly reflected in the basic requirements for these materials. Finally, having regard to the prolonged and frequent exposure to personal hygiene materials, they must not be toxic either when applied to the skin or when their vapors and aerosols enter the human body. /421

Data in the literature and our own observations indicate that these problems are not only complex, but are also incompletely solved and their study is dependent not so much on the organization and performance of special experiments as on a correct understanding of the essence of these problems.

To this must be added the special complexity of the epidemiologic aspect of personal hygiene of astronauts during long flights. Remembering that the human bacterial population comprises thousands of species of microorganisms, some useful, others harmful, the complexity of interaction of the microflora will be obvious even for a crew consisting of two persons.

Not only do we not know all the mechanisms and conditions for interaction of the autoflora of different individuals, but we also have no effective methods of stabilization or disinfection of pathogenic or conditionally pathogenic microflora directly on the human body. With this level of knowledge concerning the various conditions of prolonged human isolation it is extremely difficult both to solve the problems of prophylactic cleansing and toilet of the human skin and also to guarantee the epidemiologic well-being of crew members during long-duration space flights.

The skin, as is well known, is an important intermediary between the external environment and the organism as a whole. One of its essential functions is to protect the human organism from external influences (physical, chemical and biological).

The protective role of the skin against bacterial contamination is particularly important, not merely as a mechanical barrier (the stratum corneum), but also and, to a greater degree, by virtue of the biochemical reactions taking place on the skin surface.

We refer to the change in pH towards the acid side found on the surface layer of the skin (pH 3-5), largely attributable to the accumulation of secretions of the sebaceous glands on the skin and to chemical processes taking place in them under the influence of many different factors during prolonged isolation of the human subjects in a small closed room and prohibition of hygienic procedures. It is of course essential to point out that the importance of the sebaceous function is obvious from the existence of its central regulation (by the pituitary and sex glands). In experiments of long duration, A.M. Finogenov discovered a definite relationship between the quantity of sebum cutaneum on the human skin (layer of saturation), the pH of the skin surface and the number of bacterial cells present at a given moment on the skin. For example, in a subject with a layer of saturation of sebum cutaneum on the investigated areas of skin towards the end of a 30-day experiment amounting to $106 \mu\text{g}/\text{cm}^2$ (pH 4.6) and $61 \mu\text{g}/\text{cm}^2$ (pH 5.0), the relative number of bacterial colonies per cm^2 skin surface was (from data of L. N. Prokhorova) 3.4 and 19.7 respectively whereas for a subject with a saturation layer on these same areas of skin of $78 \mu\text{g}/\text{cm}^2$ (pH 5.0) and $43 \mu\text{g}/\text{cm}^2$ (pH 5.2), under the same conditions, the corresponding figures were 18.2 and 41.3. /422

Clearly fewer bacterial colonies were found on areas of skin with a higher concentration of sebum cutaneum, and vice versa. The at first glance paradoxical situation must now be considered that unrestricted washing of the skin, removing all products of the sebaceous and sweat glands, interferes with the protective function of the skin and cannot therefore be regarded as a rational hygienic measure.

Our investigations have shown that the dynamics of the bacterial population of the skin depend on other factors than the time of human isolation. Stabilization of the bacterial population of the skin arises primarily as a result of the accumulation of sebum cutaneum in the underclothing and on the skin surface and on the changes taking place in its chemical composition. To this it must be added that the structure of the material and the nature of the fiber used in making the underclothing undoubtedly play an important role in this process, for they influence the properties of the material to absorb the secretions of the sebaceous and sweat glands. It would be wrong in general to deny the benefit to be obtained by washing the human skin, although we must adopt a discriminating approach to this habitual procedure and emphatically reject the simple doctrine of the textbooks of personal hygiene: the more thoroughly the skin is freed from secretions of the sebaceous and sweat glands the more active its protective function. This statement, of course, is untrue not only for conditions of life and activity of astronauts, but also for many other terrestrial occupations.

Another familiar point must be added here, namely, that if there is a deficiency of lipids on the skin surface, not only the local thermoregulation and metabolism may be disturbed, but also the basic protective functions of the skin against harmful external factors.

In recent years, through the efforts of Soviet hygienists, chemists, dermatologists and microbiologists, some of the personal hygiene problems reflected in the main requirements of materials for skin hygiene of astronauts during long-duration space flights have been solved.

Ideally, the personal hygiene materials of astronauts should possess selective cleansing properties relative to external contaminants and, at the same time, they should be neutral toward biologically active substances occurring on the skin and in its surface layer. It is most important that personal hygiene materials for use by astronauts should contain certain biologically active substances (vitamins, hormones, enzymes). As regards the bactericidal action of personal hygiene materials, it must be stressed once again that the autoflora plays a highly positive role in human vital activity, for it possesses immunizing, enzyme-forming and vitamin-producing action and also antagonistic properties against certain external microorganisms. It can therefore be considered on good grounds that personal hygiene materials should possess bacteriostatic and not bactericidal activity. With respect to bactericidal properties, personal hygiene materials should possess selective action only against pathogenic and conditionally pathogenic microorganisms causing external contamination. /423

The general recommendations given below are preliminary and they by no means claim to be exhaustive. In the first place, the purpose of personal hygiene materials for use by astronauts must be stipulated.

Personal hygiene materials for astronauts are intended for systematic use during flight in order to maintain the physiological constants of the human skin at a satisfactory level, for cleansing the skin and freeing it from external contaminants and breakdown products of the secretion of the sebaceous and sweat glands, and also to maintain the astronaut's psychological optimum.

Bearing in mind the many different purposes for which personal hygiene materials are used by astronauts, these materials must satisfy the following demands:

1. Personal hygiene materials must be capable of cleansing the astronauts' skin to remove contamination by decomposition products of the secretions of the sebaceous and sweat glands, desquamated keratin scales of the epidermis, dust particles of various types, and other external contaminants.
2. These materials must promote normal skin function and maintain its optimal for attainable physico-mechanical properties and biochemical and physiological constants.
3. Astronauts' personal hygiene material must possess bacteriostatic activity against the autoflora.
4. During systematic and prolonged use of personal hygiene materials, they must not produce diseases of the skin, unpleasant subjective sensation, changes in the color of the skin, pigmented spots, hyperkeratosis, or destruction or desquamation of the epidermis. They must not sensitize the skin to ultraviolet and ionizing radiation.

5. Personal hygiene materials must possess a marked freshening action and have no odor. However, the use of very weak perfumes is permissible, in accordance with the individual preference of each astronaut. Perfumes simulating natural odors—of the forest, flowers, newly mown hay, the sea, and so on—are preferable.

6. Personal hygiene materials must not contain toxic or powerfully acting substances or volatile compounds capable of creating explosives or inflammable concentrations in the spacecraft cabin during use.

7. The constituents of personal hygiene materials must be completely compatible with the life-support systems operating on board the spacecraft and, should they enter the atmosphere of the cabin, they should be readily absorbed by the absorbents and filters used.

8. The raw and finished products used for personal hygiene materials must satisfy existing standards and technical conditions.

9. Personal hygiene materials must be prepared in a liquid or paste form and be kept in special tubes. These must bear labels indicating the rules for use of the particular material and its length of useful life.

10. Personal hygiene materials for astronauts must be prepared under sterile conditions, using minimal quantities of water in their formulas.

11. Utensils used for application of personal hygiene materials by astronauts must be compact in design, of minimal weight, and simple and reliable for use under conditions of weightlessness or abnormal gravitation.

12. The conditions of use and storage of these materials must correspond to the conditions for storage of liquid food products for consumption by the astronauts on board, which are packed in standard tubes.

OBJECTIVE EVALUATION OF DEODORIZING AND FRESHENING ACTION OF ORAL HYGIENE PREPARATIONS UNDER SPECIFIC CONDITIONS

Yu. A. Fedorov

With an increase in the duration of space flights the need has arisen for special hygiene preparations for care of the teeth and mouth, preparations suitable for use under these unusual and complex conditions.

Practical experience and the results of medical and biological research during space flights and laboratory tests have indicated the basic demands which such hygiene preparations must satisfy. /425

However, we found no specific objective tests reported in the literature suitable for the assessment of oral hygiene preparations intended for cleaning the mouth. Methods of studying the action of ordinary dental hygiene preparations are based on subjective sensations, and in the present case they are unsuitable because of the need for quantitative determination not only of the mechanical cleansing properties of the toothpaste (or other hygiene preparations), but also, and more important, the freshening and deodorizing action of the substances used. It is only if such objective methods of evaluation are available that it will be possible to produce hygiene preparations with specific action.

With the conditions of space flight in mind, attention must evidently be concentrated on the deodorizing and freshening functions of the cleansing agents. Data in the literature show that the problem of the appearance of an odor from the mouth and ways of abolishing it have received insufficient study and are still a matter for discussion [5-7].

The most probable source of an unpleasant odor from the mouth (particularly under conditions when normal cleansing of the mouth is difficult) consists of certain components of the saliva containing free sulfhydryl groups or other sulfur-containing substances, and also compounds containing amines and ammonia. An odor from the mouth may be produced by bacterial activity in the mouth itself, and above all by a pathogenic microflora. According to one authority [6], all diseases of the mouth and nasopharynx and certain diseases of the respiratory and digestive systems may produce an odor from the mouth. Ammonia products present in the saliva may also cause an odor from the mouth [4].

Other workers [3, 7] consider that the principal components of the saliva causing an odor from the mouth are substances containing free sulfhydryl groups (peptones, cysteine, reduced glutathione, etc.) or sulfur-containing compounds (methionine, cysteine, glutathione) in their composition.

On the basis of data in the literature and some personal observations, a technique of combined objective investigation of the deodorizing activity and cleansing action of certain dental hygiene products has been developed. The method is

based on determination of free and residual sulfhydryl groups, hydrogen sulfide, products of nitrogen metabolism, oxygen demand, and bacterial population in the mouth fluids and in washings obtained from the mouth before and after use of the hygiene preparation. For this purpose certain known methods of investigation [1, 2] were used, after slight modification to adapt them to the conditions of study of the mouth fluids.

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The investigations showed that quantitative estimation of the deodorizing and cleansing effect of particular hygiene preparations is perfectly feasible. In particular, they showed that the content of sulfhydryl groups varies in different persons depending on the state of the teeth, the periodontic tissues, and other factors. However, the mean content of sulfhydryl groups in saliva taken before cleaning the teeth was 2-3 times higher than after cleaning them in all subjects.

To study the content of sulfhydryl groups the mouth fluid was collected from the fasting subject, after which the teeth were cleaned with toothpaste or by rinsing with water. The mouth fluid was again collected 10 min after this hygienic procedure.

The results of investigation of the two portions were compared, and from the result the deodorizing effect of the particular hygienic measure was assessed.

To study the remaining components of the mouth fluid (ammonia, hydrogen sulfide, nitrites, nitrates), and also to determine the oxygen demand, pH, and bacterial population, three successive washings were obtained by rinsing the mouth with 100 ml distilled water. This procedure was repeated twice: in a fasting state and 10 min after hygienic cleansing of the mouth. The results were compared with each other and with the results of the previous study of sulfhydryl groups.

The total content of sulfhydryl groups in the saliva taken in a fasting state was found to vary from 6.0 to 13.30 mg % cysteine. Meanwhile, the content of total sulfhydryl groups in the saliva of the same subjects after cleaning the mouth with one of the hygiene preparations was reduced and varied from 3.0 to 8.42 mg % cysteine. This decrease is significant ($P < 0.001$). The content of residual sulfhydryl groups was also higher in saliva taken in a fasting state: 3.50 ± 0.21 before cleaning, 2.15 ± 0.16 after cleaning ($P < 0.001$).

If instead of cleaning the mouth with a hygienic preparation (toothpaste), it was merely rinsed out three times with 100 ml water, there was practically no change in the content of total and residual sulfhydryl groups.

Interesting results were obtained during the study of the content of ammonia, nitrites and nitrates in the mouth fluid and also when the oxygen demand, pH and bacterial population were determined in washings obtained from the mouth. As an illustration an example taken from one investigation in which "Lesnaya" toothpaste was used for cleaning the teeth.

As Table 2 shows, significant changes take place in the content of these substances (ammonia, nitrites, nitrates) and also in the qualitative indices of oxygen demand and pH after hygienic cleaning of the teeth.

TABLE 1.

Constituents	Before cleaning	After cleaning
Hydrogen sulfide	Absence	Absence
Ammonia, mg/liter	2	Absence
Nitrites, mg/liter	0.07	0.002
Nitrates, mg/liter	0.3	Absence
Oxygen demand, mg/liter O ₂	89.6	148
pH	6.0	5.4
Bacterial population	++++	+++

TABLE 2.

Constituents	Before rinsing	After rinsing
Hydrogen sulfide	Absence	Absence
Ammonia, mg/liter	4.0	4.0
Nitrites, mg/liter	0.2	0.04
Nitrates, mg/liter	0.7	3
Oxygen demand, mg/liter O ₂	98.3	62.7
pH	7.0	7.35
Bacterial population	++++	++++

If, however, the mouth was cleaned simply by rinsing it three times with water (100 ml), these changes were much less marked (Table 2).

It may thus be concluded from the results described above that a comparative study of the deodorizing and cleansing effect of various oral hygiene preparations used under specific conditions is a feasible proposition. Moreover, these results can be expressed quantitatively, so that the most suitable hygiene preparations can be objectively assessed and chosen. Further investigations must be carried out with a view to choosing or creating new preparations most suitable for oral hygiene.

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TOXIC GASEOUS SUBSTANCES LIBERATED FROM HUMAN FECES DURING STORAGE

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Fecal masses may be a source of pollution of the cabin atmosphere of spacecraft by various toxic substances. The quantity of feces excreted per person per day averages 150-200 g depending on the character of the food and function of the gastro-intestinal tract [1, 2].

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The feces contain 65-75% water, 3.5% nitrogen, various lipids (lecithin, coprosterol), fatty acids, carbohydrates, and a small amount of neutral fats. They also contain certain mineral substances (calcium, phosphorus, magnesium, iron, etc.) and also decomposition products of bile pigments—stercobilinogen and fecal stercobilin [3]. Dead and living bacteria and fungi account for 25-30% of the dry weight of the feces.

Fecal masses are a good nutrient medium for microorganisms. As a result of their activity, the fecal masses are decomposed with the liberation into the atmosphere of toxic and foul-smelling substances such as: ammonia and aliphatic amines, methane, hydrogen sulfide and mercaptans, indole, skatole, fatty acids (acetic, lactic, butyric, propionic, etc.), phenol and other substances [3-5]. Depending on the conditions under which fecal masses are kept, and on certain other factors, the quantity of toxic substances liberated varies. According to A. V. Palladin [6], for example, during fermentation of feces under aerobic conditions, as a result of fermentation of carbohydrates the liberation of certain organic acids (acetic, lactic, etc.) into the atmosphere is increased. Under these conditions the liberation of carbon dioxide, methane, hydrogen sulfide, indole, skatole, ammonia and its compounds also is increased. Hence, the chemical composition of the gaseous substances entering the atmosphere in the process of keeping of fecal masses is in general known.

However, there is practically no information on the quantity of the main gaseous toxic substances liberated and on changes in the normal microflora of the feces during storage. The present investigation was carried out to study these matters. At the same time, the effect of chemical conservation of feces on the intensity of liberation of the principal toxic substances was also studied. Two series of experiments were performed for this purpose. In the experiments of series I certain toxic substances liberated into the surrounding medium from fresh feces at a temperature of 18-20° were determined. The fresh feces were placed in hermetically sealed exsiccators with a capacity of 8 liters. Ammonia and its compounds, hydrogen sulfide, mercaptans, phenols, volatile organic acids, indole and skatole were determined in the air of one of these exsiccators. By means of a blower, air from the exsiccator was drawn through a special system of chemical absorbents. As the air pressure in the exsiccator was reduced, air from the room, preliminarily purified in columns with solid alkali, silica gel, pumice soaked in sulfuric acid, and hopcalite, entered it. The inlet tubes into

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the exsiccator were so arranged that the feces lay in the path of the purified air. The process of withdrawing samples lasted 2 h.

The second exsiccator was kept closed for 2 h (to obtain comparable results). Next, air was withdrawn from it into evacuated receivers for subsequent determination of carbon monoxide, hydrocarbon, oxides of nitrogen, oxygen and carbon dioxide.

The toxic substances were estimated by standard chemical methods used in industrial hygiene [7]. The contents of toxic substances were expressed per 100 g fresh feces. The results of the experiments are given in Table 1.

TABLE 1. Liberation of Toxic Substances from Fresh Feces (mg/100 g)

Ammonia and aliphatic amines	Mercaptans and hydrogen sulfide	Phenols	Indole and Skatole	Fatty acids	Oxides of nitrogen, calculated as N ₂ O ₅	Hydrocarbons calculated as CH ₄	Oxides of carbon
0,052	Traces	0,011	0	Traces	0,037	0,120	—
0,035	—	0,009	0	—	0,005	0,248	0,023
—	0	0,007	0	0,079	0,042	1,780	0,081
—	0	0,006	0	0,138	0,008	0,696	0
0,008	Traces	0,013	0	0,111	0,009	0,173	0
0,062	»	0,010	0	0,155	Traces	0,696	0
0	»	—	0	0	0,078	—	0,170
0	0	—	0	0,203	0,094	—	0,494
0,011	0	0,011	0,037	0,310	0,236	1,230	0,330
0	Traces	0,006	0,008	0,846	0,123	1,480	0
0	0,113	—	0,013	0,500	0,007	—	—
Mean 0,019	—	0,009	0,002	0,259	0,061	0,802	0,122

Commas represent decimal points.

Table 1 shows that the content of substances determined in each of the 11 experiments showed considerable variation, presumably associated with the character of the diet and the composition of the bacterial microflora of the intestine in different subjects.

At the same time, the results show that large quantities of hydrocarbons, volatile organic acids, oxides of nitrogen, ammonia, carbon monoxide, and phenols are liberated from fresh feces during the first 2 h of keeping. Mercaptans and hydrogen sulfide were found only in traces. Indole and skatole were detected episodically.

TABLE 2. Effect of Conservant on Liberation of Toxic Substances from Feces When Kept for 5 days

Quality of Toxic Substances Liberated from Feces, mg/100 g															
Group	Ammonia and aliphatic amines	Mercaptan and hydrogen sulfide	Ketones	Indole and skatole	Fatty acids	Sulfur dioxide	Phenols	Aldehydes	Oxygen of nitrogen expressed as N ₂ O ₅	Carbon monoxide	Hydrocarbons expressed as CH ₄	Number of microorganisms/g feces			
	Without conversation											On first day of experiment		On 5th day of experiment	Anaerobes
												Aerobes	Anaerobes	Aerobes	
1.	0,006	Traces	0,018	0,009	0,184	0,0410	0		0,876	0	0,945	16·10 ⁷	8·10 ⁷	9·10 ⁸	7·10 ⁸
2.	0,238	0	0,011	0,005	0,136	0	0,0430		0,012	0	0,315	35·10 ⁶	2·10 ⁸	4·10 ⁸	2·10 ⁸
3.	0,375	Traces	0,011	0	0,078	0,0060	0,008	Traces	0,074	0,063	2,630	8·10 ⁷	6·10 ⁸	3·10 ⁸	8·10 ⁸
4.	—	0	0,010	0	0,015	0	0,0440		0,035	0	0,552	6·10 ⁸	2·10 ⁸	8·10 ⁷	3·10 ⁸
5.	0,049	Traces	0,002	0	0,120	0,0050	0		—	0,051	0,964	7·10 ⁶	6·10 ⁷	—	—
Mean	0,167	—	0,010	0,003	0,107	0,0100	0,0190		0,242	0,023	1,081	—	—	—	—
With conversation															
1.	0,197	0	0,020	0,006	0,069	0	0,0280		0,038	0,298	0	10·10 ⁵	17·10 ⁷	25	0
2.	0,009	0	0,007	0	0,428	0,0120	0,0090		0,037	0,423	0,191	19·10 ⁷	25·10 ⁷	300	0
3.	0	Traces	0,035	0	0,100	0,0460	0,0060		0,016	0,243	0,152	6·10 ⁸	13·10 ⁷	130	0
4.	0	»	—	0	0,130	0	0,0130		0,033	—	1,890	3·10 ⁷	7·10 ⁸	25	4
5.	0,019	0	0,004	0	0,078	0	0		0,023	0,207	0,630	5·10 ⁸	1·10 ⁹	190	0
Mean	0,045	—	0,017	0,001	0,161	0,0120	0,011—		0,023	0,270	0,573	—	—	—	—

Commas represent decimal points.

The experiments of series II were carried out with feces stored in hermetically closed exsiccators for 5 days at a temperature of 18-20°. At the end of this time, the ammonia, mercaptans with hydrogen sulfide, phenols, indole with skatole, sulfur dioxide, ketones, aldehydes, oxides of nitrogen, carbon monoxide, and hydrocarbons were determined in the air of the exsiccators.

In addition, before the beginning of the experiment and after its end the total number of microorganisms in the fecal masses of the anaerobic and aerobic groups was determined.

To prevent putrefaction and fermentation in the feces, and also for disinfection of them, experiments were carried out with chemical conservation of the feces. Copper salt V, which in our preliminary experiments completely inactivated the microflora in fecal masses in a dose of 8-10 g/100 g/8, was chosen as the conservant. The results of these experiments are given in Table 2.

Comparison of the results shown in Tables 1 and 2 (without conservation) show that during prolonged keeping large quantities of ammonia and nitrogen-containing substances are liberated from feces. The mean quantity of phenols, indole with skatole, organic acids and hydrocarbons liberated from fresh feces was practically the same as that liberated from feces stored for 5 days.

The total number of microorganisms was increased slightly in feces kept without conservant, mainly on account of the aerobic group.

Experiments using conservant showed a sharp decrease in the number of microorganisms, in most cases no anaerobes being found, while the aerobes had died in 99.99% of cases. Determination of toxic substances showed that the effect of conservation was to reduce sharply the liberation of ammonia and oxides of nitrogen (by 4 and 10 times respectively), indicating that the conservant suppresses putrefaction and fermentation processes.

The content of phenols, indole with skatole, fatty acids, sulfur dioxide and ketones remained at approximately the same level as in the background experiment.

The considerable increase (by about 10 times) in the quantity of carbon monoxide liberated from feces when kept with conservant must be noted.

Conservants such as copper salt V are known to give rise to energetic oxidation of organic substances composing feces [9-11]. In this case the carbon monoxide is probably a product of these processes. It may thus be postulated that the liberation of toxic substances during storage of fecal masses with conservant may be considerably reduced only when the conservant presses the aerobic and anaerobic microflora, but also inhibits oxidation of organic matter.

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TOXIC GASEOUS SUBSTANCES LIBERATED FROM URINE DURING STORAGE

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The urine stored in special containers on board the spacecraft may be a potential source of pollution of the cabin atmosphere by certain toxic and foul-smelling substances. The composition and volume of urine excreted by the healthy human subject varies within wide limits depending on the character and quantity of the food and liquids consumed. The mean volume of urine produced in 24 hours is 1000-1600 ml [1, 2]. Urine consists of about 95% water, the remaining 5% being accounted for by various substances, especially urea, creatinine, phenols, uric, hippuric and oxalic acids, purine bases, ammonia and other compounds. Only a few of these substances composing urine are volatile and potentially harmful to man [3-5]. The principal members of this class are ammonia, certain amines, phenols and organic thio-acids. However, in the accessible literature we could find no information on the quantity of toxic substances possibly liberated into the atmosphere from fresh urine and from urine during storage. The present investigation was carried out to study these problems. Two series of experiments were performed. In the experiments of series I the liberation of toxic substances from fresh urine was studied.

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Urine in a volume of 200 ml was poured into a glass bottle and atmospheric air bubbled through it. The bottle was incubated at 38°C. The air bubbled through the urine was first purified in a system of columns containing hopcalite, pumice soaked in sulfuric acid, silica gel, and granulated alkali. After the bottle, absorbents were included for trapping the toxic substances for subsequent determination. Samples of air for determination of carbon monoxide and hydrocarbons were drawn off into glass gas pipets. The rate of bubbling of the air was chosen so as to ensure completeness of absorption (1.5 liters/min) of the toxic pollutants in the absorbent solutions. The air was bubbled through for 3 h.

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To determine toxic substances liberated from the urine the following chemical methods were used. Acetone, mercaptans, oxides of nitrogen, hydrocarbons, carbon monoxide and fatty acids were determined by methods developed at the Erisman Institute of Hygiene and Sanitation [1, 6]. Phenols were determined by a method based on the reaction of phenols with amidopyrin (M. F. Obukhova). Ammonia together with aliphatic amines was determined by iodometric titration.

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The quantities of toxic substances were calculated per 100 ml urine. The results of this series of experiments are given in Table 1.

The results in Table 1 show that considerable amounts of phenols, ammonia and aliphatic amines, carbon monoxide and hydrocarbons are liberated from fresh urine when pure air is bubbled through it. Mercaptans and hydrogen sulfide were found in trace amounts in only 5 of 11 samples.

TABLE 1. Liberation of Toxic Substances from Fresh Urine

Quantity of toxic substances, mg/100 ml urine						
Ammonia and aliphatic amines	Phenols	Mercaptans and hydrogen sulfide	Acetone	Fatty acids	Carbon monoxide	Hydrocarbons calculated as methane
0,069	0,014	—	—	—	0,068	0,017
0,023	0,012	—	—	—	0,140	0,038
—	0,029	Traces	—	—	0,015	0,055
0,014	0,041	»	0,032	—	0,076	0,083
0,002	0,026	»	0,009	—	—	0,031
0,007	0,045	»	0,029	—	0,046	0,038
0,004	0,033	»	0,008	—	0,070	0,010
Traces	0,013	—	Traces	0,033	0,094	0,021
»	0,017	—	0,003	—	0,039	—
»	0,013	—	Traces	Traces	0,006	—
»	0,016	—	Traces	»	0,003	—
Mean						
0,012	0,024	—	0,010	—	0,055	0,033

*Content of substances in mg/liter air bubbled through. Commas represent decimal points.

TABLE 2. Liberation of Toxic Substances from Urine Kept for 3 Days in a Closed Container

Quantity of toxic substances, mg/100 ml urine							
Ammonia and aliphatic amines	Phenols	Mercaptans and hydrogen sulfide	Acetone	Fatty acids	Carbon monoxide	Hydrocarbons calculated as methane	Oxides of nitrogen calculated as N ₂ O ₅
Traces	0,006	Traces	—	—	0,026	0,049	0
0,001	0,007	»	Traces	0,058	0,028	0	0
0,005	0,008	»	0,002	0,028	0,017	0,034	0,003
Traces	0,007	—	Traces	0,012	0,036	0,149	Traces
0,001	0,006	—	»	0,012	0,039	0	»
0,094	0,005	—	0,0004	0,020	0,071	0,085	0,0005
Traces	0,006	—	0,0008	0,035	—	0,151	0,0003
Mean							
0,014	0,006	—	0,0006	0,028	0,035	0,094	0,0013

*Content of substances in mg/liter air bubbled through. Commas represent decimal points.

In the experiments of series II an attempt was made to determine the changes in the composition and quantity of toxic substances liberated from urine when kept for 3 days at a temperature of 18-20°. Urine in a volume of 500 ml was kept in hermetically sealed 5-liter glass bottles for three days. Next, samples of air were withdrawn from the bottles through a system of vessels with absorbent solutions and into gas pipets. The results of these experiments are given in Table 2.

As Table 2 shows, the air above the urine stored for 3 days is contaminated by several toxic products. In these experiments the same substances were found as in those of series I. In addition, oxides of nitrogen were found in the air samples. Comparison of the results of the experiments of series I and II shows that the mean content of ammonia and aliphatic amines was practically the same in both cases. Liberation of phenols and acetone from urine during keeping was significantly less than when pure air was bubbled through fresh urine. Much larger quantities of fatty acids are liberated from urine stored for 3 days than from fresh urine.

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SEARCH FOR PREPARATIONS FOR PRESERVATION OF FECES FOR USE UNDER SPACE FLIGHT CONDITIONS

L. N. Rogatina

Among the many measures directed toward the creation of satisfactory flight conditions, a special place is occupied by the prevention of bacterial contamination and, in particular, the prevention of putrefaction and fermentation of excreta by the action of microorganisms.

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In my opinion, only substances free from pungent odor and toxicity are suitable for use for preservation and deodorization under space flight conditions.

Chlorine preparations such as chloride of lime, calcium hypochlorite, chloramine, etc., and phenol preparations (cresol, lysol, phenol and their derivatives in combinations with alkalies) are most commonly used for disinfection of human excreta at the present time.

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I refrained from using these preparations because of their strong odor, toxicity, the fact that some are branded articles, and they corrode metals. Their use even in exceedingly low concentrations in a small, confined space would make it impossible for man to remain there.

To preserve food products and biological preparations, acids (boric, sulfosalicylic, citric), salts (sodium chloride, sodium citrate), and broad-spectrum antibiotics (penicillin, chlortetracycline, oleandomycin, niacin, etc.) are used.

Quaternary ammonium compounds are being increasingly used in practice for the disinfection of dishes, surfaces, linen, and so on [2, 3].

Ye. N. Nikiforova disinfected a fecal suspension with the preparation "Kata-min A," belonging to the group of quaternary ammonium compounds and used in containers of aircraft toilets. We therefore tested several preparations from this group for the preservation of feces.

Salts of silver, copper and manganese and also hydrogen peroxide are used for water preservation. The use of salts of heavy metals (copper sulfate and chloride) for disinfection and for prevention of fermentation and putrefaction of feces has been known for a long time.

G. F. Gauze [1] considers that during prolonged contact between biological materials and silver salts, active ions enter the medium with gradually increasing intensity, replacing bound ions and thus ensuring prolonged anti-bacterial activity.

We concluded from data in the literature that for the purposes of preservation of feces under space flight conditions, it is most rational to concentrate

TABLE 1. Effect of Preparations Added to Feces on Effectiveness of Preservation

Preparation	Quantity of preparation added to 100 g feces	Results of seedings after:		
		5 days	10 days	15 days*
Silver fluoride	1,0	+	+	+
	3,0	+	—	—
	5,0	—	—	—
	8,0	—	—	—
Silver nitrate	1,0	+	+	+
	5,0	+	—	—
	6,0	+	—	—
	8,0	—	—	—
	10,0	—	—	—
Silver sulfate	5,0	+	—	—
	7,0	±	—	—
	8,0	—	—	—
	10,0	—	—	—
Silver oxide	1,0	+	+	±
	5,0	±	—	—
	8,0	—	—	—
Copper salt "V"	1,0	+	+	±
	5,0	±	—	—
	7,0	—	—	—
	8,0	—	—	—
Copper sulfate	5,0	+	+	+
	10,0	+	+	—
	20,0	±	—	—
	25,0	±	—	—
	30,0	—	—	—

*Starting from 20 days and until 12 months none of the preparations weakened the preservative effect.

Commas represent decimal points.

attention on the study of preparations from the following groups of chemical compounds: salts of heavy metals, quaternary ammonium compounds, antibiotics and oxidizing agents.

Altogether 24 preparations were studied under laboratory conditions.

Samples of feces (50 g) were placed in sterile glass dishes and sprinkled with the test preparations in doses of 10 g/100 g feces. After mixing the feces with the preservative with a glass rod, the samples were placed in a dark cupboard at room temperature for 100 days. The temperature was recorded daily. Samples of feces without addition of preservatives acted as control. The effectiveness of preservation was assessed by taking seedings from the experimental and control samples on nutrient media (meat-peptone agar, meat-peptone broth, Endo's medium, liver broth with cysteine).

Seedings were made 5, 10, 15, 20, 25, 30, 60 and 100 days after the beginning of contact between the feces and test materials. The results of tests of preservatives of the feces for 100 days at the rate of 10 g/100 g feces are given in Table 2.

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TABLE 2.

Effective	Ineffective	Ineffective
Silver fluoride	Sodium chloride	Cetyloctadecylpyridinium bromide
Silver nitrate	Potassium permanganate	Cetyloctadecyltrimethylammonium bromide
Silver sulfate	Boric acid	C-4
Silver oxide	Calcium oxide	Cetyloctadecyltriethylammonium bromide
Copper salt "V"	Penicillin	Hydrogen peroxide
Copper sulfate	Synthomycin	
Crystalline iodine	Chloramphenicol	
Feziomon	Erythromycin	
Katamin "K"	Oleandomycin	
PTA		

We next studied the efficacy of six selected preparations suitable for preservation of feces and determined their minimal dose. The results of these experiments are shown in Table 1.

It is clear from Table 1 that preservation of feces by silver (fluoride, nitrate and sulfate) and copper preparations is possible with a dosage of 5-8 g/100 g feces. Copper sulfate has a weaker action, being effective only in a dose of 30 g.

Long exposures up to one year (end of the period of observation) did not weaken the preservation effect.

The specific odor of feces was considerably weakened (deodorizing effect), but it proved impossible to remove the odors arising from chemical decomposition of the organic substances completely.

When the preserved samples were dried, their odor disappeared completely.

If the cost of the preparations is compared with their efficacy, in our opinion the advantage rests with copper salt "V".

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MEDICAL PROVISION FOR LONG SPACE FLIGHTS

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Space flight is always associated with the overcoming of gravitational forces, /439 and the weight and dimensions of the spacecraft at each stage of space exploration are restricted. For this reason medical provision for space flight is based on the principles of unification and universalization of medical equipment and the reduction in their weight by replacing metallic parts of instruments by synthetic products and by discarding ballast material from standard therapeutic forms. However, while adhering to these principles, it is impossible to include in the dispensary on board the spacecraft all the variety of medical equipment used on earth. Furthermore, this is unnecessary. The presence of medicines for the treatment of diseases not encountered during space flight (some chronic and endemic diseases, diseases associated with specific ages, diseases caused by insect and snake bites, etc.) would simply complicate the furnishing of such a dispensary. On board the spacecraft there must be only those medicines essential for treating the most probable or all the possible diseases and disorders arising during flight. These include the sequelae of physiological changes observed during space flights and in experiments simulating space flights (changes in endocrine influences, in the hemodynamics, the coagulation of the blood, decalcification of bones, dehydration of tissues, disorientation of the kinetic receptor apparatus, and so on).

A sudden increase in radiation associated with chromosphere activity of the sun may produce radiation sickness. Although as a result of the combined action of cosmic factors during a prolonged flight new and as yet unknown diseases may arise, the most likely event is the appearance of diseases encountered on earth, particularly in isolated groups of sailors and polar explorers [1]. Such persons are exposed for long periods to the action of extreme conditions, they remain for long periods under conditions close to those of space flight, and their morbidity may serve for guidance when forecasting morbidity among astronauts during long space flights, and hence, for forecasting equipment and materials necessary (P. V. Buyanov, V. G. Terent'yev, G. L. Yaroshenko). On these grounds, the probability of appearance of certain diseases has been calculated mathematically /440 and as a function of length of stay under extreme conditions (duration of space flight) and of the number of persons involved.* The calculation was made from morbidity data among polar explorers during wintering at stations within the Antarctic continent. All the explorers had passed a preliminary medical examination, including tests of tolerance to moderate degrees of anoxia in a pressure chamber, and were accepted as suitable for activity connected with their occupation. They were mainly young (under 40 years of age).

An attempt was made to determine the probability of illness among members of the crew of a spacecraft during a flight of long duration. The character of this investigation is determined by the type of statistical model of distribution

* Crews consisting of men are envisaged.

which should be used for its solution. The Poisson distribution is a suitable model for this purpose, and is the one usually used to study rare events.

When using Poisson's law, the occurrence of the expected event is simulated by a point falling within a given segment l along the axis ox . In this case the probability of occurrence of m points in segment l is expressed by the formula

$$P_m = \frac{(\lambda l)^m}{m!} e^{-\lambda l},$$

where λ represents the mathematical expectancy of the number of points per unit of length (or the statistical probability of the event).

The probability that no point shall fall within the given segment l is given by:

$$P_0 = \frac{(\lambda \cdot l)^0}{0!} e^{-\lambda l} = e^{-\lambda l}.$$

Finally, the probability R_1 that any one point shall fall within the given segment is given by:

$$R_1 = 1 - P_0 = 1 - e^{-\lambda l}.$$

Let us now turn to the conditions of our investigation. We can state that the probability of any one attack of a certain disease among members of the crew during a given time interval can be expressed by the analogous formula:

$$R_1 = 1 - e^{-(n \cdot \lambda_i \cdot \tau)},$$

where n represents the number of members of the crew; λ_i the statistical probability of an attack of the given disease; and τ the assigned time interval.

The last formula is the basis for our calculations. By substituting different values of n , λ_i and τ , values of the probability that members of the crew will suffer from a particular disease can be calculated for flights of different durations.

The results of calculations using Eq. (4) for certain diseases are given in Table 1.

As Table 1 shows, the probability of occurrence of diseases rises with an increase in the number of persons and in the duration of their stay under extreme conditions. The probability of certain diseases for a crew of 10-15 persons, moreover, tends toward unity with an increase in length of exposure, i. e., these diseases are found during space flight under certain conditions and astronauts must be prepared to give medical assistance should they appear. The least

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TABLE 1. Probability of Occurrence of Certain Diseases as a Function of Number of Crew Members and Periods of Duration under Extreme Conditions

Illness	Duration of flight, months																			
	1					3					6					12				
	1*		3	10	15	1*		3	10	15	1		3	10	15	1	3	10	15	
	1*	3	10	15	1*	3	10	15	1	3	10	15	1	3	10	15	1	3	10	15
1. Angina	0,00	0,02	0,05	0,08	0,01	0,03	0,10	0,15	0,03	0,09	0,27	0,38	0,06	0,18	0,48	0,62	0,06	0,18	0,48	0,62
2. Pulmonary tuberculosis	0,00	0,00	0,02	0,03	0,00	0,01	0,03	0,05	0,01	0,03	0,09	0,14	0,02	0,06	0,18	0,25	0,02	0,06	0,18	0,25
3. Wounds, contusions, strains	0,01	0,02	0,09	0,14	0,02	0,06	0,17	0,25	0,06	0,16	0,44	0,58	0,11	0,30	0,68	0,82	0,11	0,30	0,68	0,82
4. Diseases of the central and peripheral nervous system and mental disorders	0,01	0,03	0,10	0,16	0,02	0,07	0,20	0,28	0,07	0,18	0,49	0,64	0,12	0,33	0,74	0,87	0,12	0,33	0,74	0,87
5. Diseases of the lungs of nontuberculous origin	0,01	0,02	0,09	0,12	0,02	0,05	0,16	0,24	0,05	0,15	0,42	0,56	0,10	0,28	0,66	0,81	0,10	0,28	0,66	0,81
6. Diseases of heart muscle and vessels	0,02	0,06	0,19	0,27	0,04	0,12	0,34	0,47	0,12	0,32	0,72	0,85	0,22	0,53	0,92	0,98	0,22	0,53	0,92	0,98
7. Diseases of digestive organs	0,00	0,00	0,02	0,03	0,00	0,01	0,04	0,06	0,01	0,04	0,12	0,18	0,02	0,08	0,23	0,32	0,02	0,08	0,23	0,32
8. Acute appendicitis	0,00	0,01	0,04	0,06	0,00	0,02	0,08	0,12	0,02	0,08	0,23	0,32	0,05	0,14	0,40	0,54	0,05	0,14	0,40	0,54
9. Diseases of bones, muscles, joints	0,02	0,08	0,23	0,33	0,05	0,15	0,41	0,54	0,15	0,38	0,79	0,91	0,27	0,61	0,96	0,99	0,27	0,61	0,96	0,99
10. Suppurative diseases of the skin and subcutaneous cellular tissue	0,02	0,06	0,18	0,26	0,04	0,12	0,33	0,45	0,11	0,30	0,70	0,84	0,22	0,51	0,91	0,97	0,22	0,51	0,91	0,97
11. Stones in the kidneys and urinary tract	0,00	0,00	0,01	0,02	0,00	0,00	0,02	0,03	0,00	0,02	0,06	0,10	0,04	0,04	0,12	0,18	0,04	0,04	0,12	0,18
12. Intestinal dyskinesias	0,00	0,02	0,08	0,12	0,02	0,05	0,16	0,22	0,05	0,14	0,40	0,54	0,10	0,27	0,64	0,78	0,10	0,27	0,64	0,78
13. Diseases of the teeth and gums	0,04	0,12	0,34	0,46	0,08	0,22	0,56	0,71	0,21	0,52	0,91	0,98	0,38	0,77	0,99	0,99	0,38	0,77	0,99	0,99
14. Sleep disturbances	0,03	0,10	0,30	0,41	0,07	0,19	0,50	0,65	0,19	0,46	0,88	0,96	0,34	0,72	0,95	0,99	0,34	0,72	0,95	0,99

* Number of persons.

Commas represents decimal points.

probability to be taken into account in the calculation depends (according to the "principle of practical certainty") on the risk presented by the particular disease. The more dangerous the disease, the lower the probability of its appearance which must be taken into account, and conversely, the less the risk to health and working capacity presented by a disease, the greater its probability which can be disregarded. For example, if a group of 3 persons stays under extreme conditions for three months (Table 1), the probability of appearance of diseases of the heart and blood vessels is very low (0.12). However, considering the severity of the course and difficulty of diagnosis of these diseases, this probability of their occurrence must nevertheless be taken into account, and medical assistance must be regarded as essential. In the future, during the conquest of space, demands made on the functional capacity and training of astronauts are bound to increase, conditions of flight will be changed, and this must evidently result in some lowering of standards concerning the state of physical health. This may result in an increase in the number of cases of illness during prolonged space flights, and the problem of medical provision for them will become more urgent still.

As a result of the use of this approach to the problem of medical provision for prolonged space flights, taking into account the complete and systematic data available on morbidity of small groups of polar explorers, sailors making long single-handed voyages, experimental subjects, astronauts, and so on, we can:

- a) forecast the most probable disturbances and diseases and the time of their appearance;
- b) provide the necessary measures for their treatment and control;
- c) determine the level of training of astronauts necessary for rendering medical assistance during flights of different durations and for crews consisting of different numbers of persons; and
- d) determine flight conditions under which a physician must travel on board the spacecraft.

The suggested method may prove useful for the specification of optimal medical provision for expedition for whatever purpose.

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PHYSIOLOGICAL ASPECTS OF THE USE OF HYPOTHERMIA IN SPACE MEDICINE

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The problem of controlled modification of reactivity of the living organism by artificial hypothermia has long attracted the attention of investigators. The first accounts of the effective use of hypothermia in medical practice were given near the middle of last century [4, 21, 32]. However, until recently it could not be regarded as finally solved. Many theoretical and practical aspects of artificial hypothermia of the warm-blooded organism remained debatable. /443

Considerable advances in the field of study of pathophysiology of states with a reduced body temperature were achieved by the study of cooling and freezing [1, 6, 20], and also of the seasonal hibernation and anabiosis [2, 12, 17].

The most active period of study of the pathophysiology of artificial hypothermia of animals and man have been the last few decades [28, 29, 39, 43, 44, 47].

Many investigators have shown conclusively that artificial hypothermia is an effective means of treatment of anoxia and shock. Deep hypothermia has proved of great promise for prolonging the period of reversible changes during clinical death.

Because of the practical needs of anesthesiology and surgery, many investigations have been directed toward the study of the deepest possible reversible hypothermia for comparatively short periods.

The problem of prolonged hypothermia, which was widely studied in the 1950's [33-35, 42, 45], at present has few investigators. However, statements continue to appear in the literature on the great practical value of moderate prolonged hypothermia with complete preservation of vital activity of the organism. The suggestion has been made that hypothermia is potentially useful in space research [8, 17, 19, 27, 32, 41].

Experimental investigations have demonstrated an increase in the resistance of the artificially hypothermic organism to influences such as ionizing radiation and overloading [3, 5, 9-11, 13, 25, 26, 30, 46]. In addition, artificial hypothermia or artificial hibernation may be very convenient for the transportation of biological objects on board the spacecraft.

The methods of producing artificial hypothermia widely used in clinical practice are cumbersome and technically difficult, and for that reason they are unsuitable for space research. Comparison of data in the literature on methods of moderate hypothermia does not permit preference being attached to any one of them, because of the largely contradictory opinions expressed. The main disagreements are concerned with the desirability and depth of hypothermia, the /444

method of cooling and, above all, the method of preventing excessive reflex reactions of the organism preventing the development of hypothermia.

Nowadays most authors use a combination of pharmacological blocking and cooling. However, the composition of "lytic mixtures" is not finally settled, and some investigators do not recommend their use at all, for they prevent operation of physiological control mechanisms during the period of recovery of functions on reheating.

The description of the character of the pathophysiological changes is extremely variegated for different authors frequently cite results obtained by different methods of artificial hypothermia. The most careful study has been made of the central nervous system and circulatory organs. Much less attention has been devoted to changes in respiration. This is because with the very first studies, marked disturbances of external respiration were established. Without going more deeply into their study, investigators followed the most logical paths from the point of view of clinical practice. To prevent possible respiratory anoxia, it became the common practice to use compensated, and later artificial, respiration against a background of deep curarization, more especially because this also solved a second, no less important problem, the prevention of reflex shivering. Naturally we can discuss a method of artificial hypothermia capable of use under space flight conditions on an actual basis only if it responds to a number of essential conditions. One of the most important of these is the following: the safety and reliability of the method, which is able to produce prolonged and easily controlled reversible hypothermia with a considerable decrease in reactivity of the organism. Obviously elements of the method such as artificial respiration and, in particular, the artificial circulation are ruled out. It thus follows that investigators are confronted by the problem of developing new methods of induction of moderate hypothermia responding most completely to the demands presented. Most attention must be paid to the more complete study of safety limits of the depth and duration of artificial hypothermia with maintenance of spontaneous respiration and circulation. Some attempts at solving these problems have been made by the present authors in experiments on albino rats and dogs.

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Under standard conditions of external air cooling, various methods for preventing reflex reactions of the organism to the action of cold were tested. Different combinations of a "lytic mixture," short-action barbiturates, urethane anesthesia, relaxants, and a modified gaseous environment (hypercapnia and hypoxia) were used. Attention was concentrated on the study of the functions of gas exchange, respiration and the circulation.

The investigations revealed considerable differences in the course of hypothermia depending on the method used. Not one of the combinations of the substances mentioned completely prevented undesirable symptoms of stress on mechanisms of physiological compensation in the first stages of hypothermia. In all the experiments the first general adaptive response of the animal (as described by I.R. Petrov) was clearly observed, in the form of quickening of the heart rate, quickening and strengthening of respiration, some increase in the oxygen demand, muscular tremor, and so on. However, the severity and duration of this phase of hypothermia were due to the methods used to block reflex activity, and they enabled a comparative analysis to be made of the efficacy of

these methods. In experiments on rats, for instance, the best method of blocking thermoregulatory mechanisms during cooling was found to be an environment with a gradually increasing level of hypercapnia and hypoxia [8]. The first general adaptive reaction of the animal under these conditions was short in duration and ill defined. Besides the subsequent deep depression of all the principal vitally important functions of the organism, the ability for hypothermia to undergo rapid reversal persisted for a long time. Compared with other methods studied, this gave the highest oxygen level in the arterial blood, indicating not only the efficiency of external respiration, but also the more optimal conditions of maintenance of homeostasis. The enzyme systems of tissue respiration (succinate dehydrogenase and cytochrome oxidase of the liver) showed high resistance to hypothermia, and their activity remained unchanged when the body temperature of the animals had fallen to 20°. Moreover, the liver succinate dehydrogenase activity corresponded to the changed temperature of the tissue environment. For example, in rats cooled to 20° the oxygen demand was about one-fifth of its initial level, and the succinate dehydrogenase activity was lowered on the average of one-quarter. Having regard to the high resistance of tissue respiration mechanism to hypothermia, we were justified in assuming that during artificial hypothermia with maintenance of natural respiration, pathophysiological disturbances arise as a result of disturbances of functions of the organs supplying oxygen to the tissues.

The high resistance of albino rats, cooled under conditions of gradually increasing hypercapnia and hypoxia, to the action of prolonged radial acceleration, to hypoxic hypoxia, and to a high degree of rarefaction of the atmosphere (experiments carried out jointly with V.S. Oganov and N. N. Timofeyev) demonstrated the efficacy of the condition obtained.

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Hypothermia produced by cooling with other methods for preventing reflex reactions greatly reduced the resistance of animals to overloading.

In experiments on dogs, the best method of preventing excessive reflex responses interfering with the development of hypothermia was by means of a neurovegetative block by "lytic mixture" (chlorpromazine 5 mg/kg, pipolphen 5 mg/kg, trimeperidine 1 mg/kg, and methyldiazine 0.5 mg/kg), combined with short-action barbiturate and controlled carbon dioxide anesthesia. The physiological indices studied showed considerable variation, but their degree differed from those in experiments using hypothermia under urethane anesthesia (Table 1).

The minute volume of respiration and the respiratory quotient, for instance, remained at a higher level whereas the oxygen consumption was lower. The function of the circulatory organs was inhibited much more deeply; the minute volume of the heart and the mean arterial blood pressure fell more than during urethane anesthesia, but the tissue oxygen supply was disturbed to a lesser degree. Despite the marked decrease in oxygen capacity of the blood because of "chlorpromazine" hydremia, the utilization of hemoglobin was more complete and the arterio-venous oxygen difference showed a much smaller change. All this indicated a less severe disturbance of homeostasis in the animals after blocking of thermoregulatory mechanisms by the "lytic mixture" and short-action barbiturates and, consequently, more favorable conditions for hypothermia to run its course than in the case of cooling during urethane anesthesia.

TABLE 1. Results of Comparison of Some Physiological Indices During Artificial Hypothermia in Dogs

Indices	Methods of blocking reactions to cooling			
	Lytic mixture and hexobarbital (50 mg/kg)		Urethane anesthesia (2.0 g/kg)	
	32-30°	27-25°	32-30°	27-25°
Minute volume of respiration, liters . .	1,1 * $\pm$ 0,23	0,81 $\pm$ 0,14	1,08 $\pm$ 0,22	0,72 $\pm$ 0,17
O ₂ consumption, ml/kg/min	5,0 $\pm$ 0,70	2,0 $\pm$ 0,53	6,09 $\pm$ 0,56	5,52 $\pm$ 1,96
Respiratory quotient	0,53 $\pm$ 0,02	0,53 $\pm$ 0,03	0,52 $\pm$ 0,04	0,46 $\pm$ 0,04
Hematocrit index	30,1 $\pm$ 3,32	34,4 $\pm$ 2,7	69,3 $\pm$ 4,83	75,5 $\pm$ 6,06
O ₂ concentration in arterial blood, v% . .	15,58 $\pm$ 1,34	13,85 $\pm$ 0,73	24,32 $\pm$ 0,92	23,12 $\pm$ 0,79
Arteriovenous differences in O ₂ , v%	6,16 $\pm$ 0,17	6,11 $\pm$ 0,82	4,62 $\pm$ 1,08	4,52 $\pm$ 1,47
Minute volume of heart, liters	0,58 $\pm$ 0,089	0,38 $\pm$ 0,089	0,75 $\pm$ 0,134	0,91 $\pm$ 0,114
Heart rate, % of initial	70,6 $\pm$ 3,27	43,6 $\pm$ 2,16	102,1 $\pm$ 8,54	61,0 $\pm$ 4,59

*Mean value $\pm$ mean error.

Commas represent decimal points.

The efficacy of the use of hypercapnia has been demonstrated clearly during cooling of rodents [14, 16, 24, 36]. Only occasional successful results of experiments on other species of animals have been described [25, 40]. In this connection our experiments on dogs were exploratory in character. The degree of hypercapnia varied from 5 to 60%, and various combinations of hypercapnia with the "lytic mixture" and short-action barbiturates were used; from the results of these experiments, the use of carbon dioxide anesthesia for blocking thermoregulation in dogs can be regarded as effective. Inhalation of hypercapnic gas mixtures (30-40% CO₂) made it possible to reduce the dose of barbiturates substantially (to 20-30 mg/kg), while maintaining an adequate depth of anesthesia. The advantages of inhalation anesthesia were preserved, and the animals reacted precisely to changes in carbon dioxide concentration in the inhaled gas mixture, so that the process of hypothermia could be actively modified at any stage. The temperature limits for cessation of activity of the respiratory center were unchanged, but the volume of the pulmonary ventilation

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remained higher throughout the experiment. Hypercapnia had a very favorable effect during recovery from hypothermia. Inhalation of a gas mixture containing 5-15% CO₂ blocked the developing motor excitation and the muscular tremor and thus facilitated the more economic utilization of energy resources in the body during restoration of the normal rhythm of vital activity.

Investigation of the mechanisms of disturbance of respiration in dogs in a state of artificial hypothermia showed that, just as in experiments on rats, the processes of tissue respiration showed high resistance to the action of cold and remained capable of utilizing oxygen at near-background level.

The duration of reversible hypothermia in our experimental conditions varied from a few hours to one day. The temperature limits of stabilization of artificial hypothermia were small and differed both from the comparative physiological standpoint and in animals of the same species. Optimal levels of the rectal temperature at which hypothermia could be prolonged were 18-20° for rats and 23-25° for dogs, isothermia being maintained with an external environmental temperature of 15-18°. Cooling the animals below these temperature limits led to disturbance of the mechanisms of physiological regulation, one of the first manifestations of which was disturbance of the rhythm, followed by cessation of spontaneous respiration, after which all subsequent disturbances in the body developed rapidly. The symptom-complex of disturbance of physiological regulation as a rule developed within a few minutes and recovery from hypothermia was possible only if rapid and energetic measures were taken.

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The production of artificial reversible hypothermia with considerable depression of the vital functions yet with essential preservation of homeostasis is a matter of considerable difficulty. Not one of the known techniques can satisfy the demand which must be presented if the use of hypothermia under the conditions of long-term space flights can be met in the future. Moreover, it would obviously be unjustified to attempt to develop a universal method applicable to all biological objects without regard to their level of physiological organization.

It is difficult to judge the effectiveness of the state of artificial hypothermia obtained by examination of data such as the body temperature, the degree of lowering of the intensity of metabolic processes, and other physiological indices recorded in hypothermic animals. Under these circumstances the characteristics of development of hypothermia are very important, especially the degree of manifestation of its first (compensatory) phase, resulting from the use of the method of blocking reflex reactions to cooling.

Data in the literature and results of our own experiments can thus do no more than indicate some pathways for development of methods of artificial hypothermia for use in rats and dogs. The final solution of the problem requires extensive experimental research. Together with problems concerned with the development of methods for blocking thermoregulatory mechanisms, considerable attention must be paid to the investigation of the possibility of automation of the processes used in producing artificial hypothermia, to investigation of control over the basic physiological functions, of prolonged maintenance of the state of hypothermia and recovery from it. The investigations of Ye. V. Maystrakh and co-workers [14] and of others are of considerable interest in this respect.

The practical use of artificial hypothermia during space flights will evidently be for several purposes. The most important of these are as follows: transportation of biological objects during flights of long duration, and their protection against the action of extreme factors (anoxia, radiation injury, etc.). The possibility is not ruled out that in future such a method of biological protection may also be used by the members of the spacecraft crew during long flights in various emergency situations calling for strict economy in the use of oxygen, water and food products. A solution to the problem may be found by developing a method of controllable superficial hypothermia of the "artificial hibernation" type. The energy gained in this manner may be much greater, for as numerous investigations by other workers have shown, the safe duration of artificial hibernation is many times greater than the possible duration of reversible artificial hypothermia. Should the need for the state of depressed vital activity be dictated by a single purpose--economy in oxygen and food, this will be the more promising method.

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BIOTECHNOLOGY

RESULTS OF PHYSIOLOGICAL AND ECOLOGICAL INVESTIGATIONS OF CHLORELLA CULTURES AS A LINK IN A CLOSED ECOLOGICAL SYSTEM*

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The use of the principle of biological circulation of matter as a means of life support for the crew of spacecraft was suggested by K. E. Tsiolkovskiy [13] as a natural continuation of his work on the theoretical basis of interplanetary flights. It is worth noting that the first attempts at an experimental approach to this problem were undertaken as long ago as in 1915-1919 by A. F. Tsander, an engineer who was one of the founders of rocket construction in the USSR. In experiments to grow vegetables on artificial soil substitutes (charcoal), he used human metabolic products for their nutrition [12]. These were evidently the first experimental ecological investigations directly aimed at meeting astronautical needs. /451

At the present time the idea of creating a closed cycle of circulation of matter is not only a subject of experimental research, but is also embodied in design work undertaken by many laboratories in several different countries.

Among the first components suggested for biological life-support systems in spacecraft were unicellular algae and, in particular, the genus Chlorella, which is now regarded as a probable element in the photosynthetic link included in the closed ecological system. /452

This paper describes a study mainly of the material balance of that part of the photosynthetic link which can be based on the use of unicellular algae. When this problem is examined certain general aspects of the simulation of ecological systems must not be overlooked, for they determine the main pathways to be followed in the development of individual functional links. In contrast to living nature, which at all stages of its evolution was an integrated system and never appeared by synthesis from preexisting elements, we are apparently compelled to follow a path of "one-act creation," creating a functionally intact system from existing elements adapted for the performance of function when incorporated in another, already acting system, nature as it exists on Earth.

Because of the unprecedented complexity of this problem, the choice of a general method of solution is extremely important. Obviously the method of direct synthesis by trial and error is unsuitable here because of the extreme complexity and the not always predictable volume of direct connections and feedbacks between the elements of the constituted system. In this case the only suitable method is by the planned construction of a system as a whole and of its corresponding

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components on the basis of preliminary calculations. In other words, the closed ecological system must be created from the very beginning as an integrated system with perfectly definite tasks and functional characteristics, determining its composition and structure and the main parameters of its component elements.

It follows from what has been said that the design of experimental models of closed ecological systems is largely based on the study and quantitative description of functional connections between preliminarily selected objects which determine their position, their requirements and their external work in the system of rotation of matter and energy, their ecological "niche."

We must therefore study and describe the input and output characteristic of the hypothetical elements of the future system. Such characteristics are an essential condition for the preliminary calculation and the practical accomplishment of models of biological systems for any definite purpose.

The following principal characteristics may be stipulated, as essential for calculations and model construction, for the link consisting of unicellular algae, the subject of this report.

A. Input parameters.

Energy: Optimal and extreme values of intensity and of spectral composition; intake regime, specific consumption.

General conditions of function: Optimal and extreme values of temperature, acidity of medium, dynamic conditions of cultivation—mechanical overloads, pressure, and their differentials.

Material requirements: Optimal and extreme values of concentration of carbon dioxide and mineral food elements, their specific consumption.

B. Output parameters.

Energy: The free energy available in the system expressed as a ratio of the incident and absorbed energies.

Material output: Specific productivity with respect to oxygen and biomass, chemical composition and food value of biomass, its coefficient of useful utilization in the system.

Side processes: Pollution of the atmosphere with incidental contaminants, accumulation of products of cell metabolism and destruction in the nutrient medium.

In addition, the provision of automatic control in the system requires the study of some special processes including the general properties of the link in the system of information and control: the informative value of individual parameters of the link, frequency characteristics of spontaneous and forced oscillations, the parameters of transitional processes and transmission functions, etc.

This report summarizes briefly the results of an investigation of characteristics of the material balance of Chlorella cultures essential for the determination of their place and their requirements and of the role of matter.

Data are also given relative to the dynamic properties of Chlorella cultures as an object for control.

In the Soviet Union the study of cultures of unicellular algae for practical use in air regeneration systems was founded on the investigations of N.S. Gayevskaya, V.V. Pinevich, V.A. Chesnokov, N.N. Verzilin and others [1, 10, 14], and also on work by V.Ye. Semenenko, M.G. Vladimirova and A.A. Nichiporovich [11].

The first attempts at supporting the gas exchange of animals and man by photosynthesis of Chlorella in closed gas-exchange systems were made in 1960-1961 (G.I. Meleshko, Ye.K. Lebedeva, T.B. Galkina and others). Later they carried out complex investigations of Chlorella cultures as a possible link in a closed ecological system.

The first experiments on the support of animal gas exchange led to the conclusion that the successful experimental simulation of ecological systems requires the most accurate knowledge possible of the material and energy requirements, the conditions of function, and the material outputs of each element of the system.

The direct application of physiological data to the creation of a stable and highly productive biotechnologic process in populations of algae is hampered by the fact that their general physiological characteristics do not allow for the transforming effect of the population on the habitat. At the same time, as a result of this effect, the external environmental conditions do not always remain constant within the population but deviate from the initial value at the borders of the territory which it occupies (the biotope). The greater the density of the population and its specific productivity, the greater this deviation.

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Because of this factor, intrapopulation gradients of the properties of the medium arise, and this is an important feature distinguishing the population as a system from a simple multiplicity of individuals. For the quantitative assessment of functional connections of a given link in the ecological system it therefore became necessary to organize special experimental ecological investigations using as object a highly productive population of the species under study, with all the special features of the intrapopulation relationships of individual organisms and the relationship of the population as a whole with the surrounding medium.

To obtain the essential data, a group of workers under G.I. Meleshko's direction carried out combined investigations of the material balance of Chlorella when cultivated in high-productivity photosynthetic reactors with a closed air system [3, 6-9].

An important characteristic of the photosynthetic link is the gas-exchange coefficient: the ratio between the volume of carbon dioxide utilized and the volume of oxygen produced, which must correspond to the respiratory quotient of the consumer links of the ecological system. Experimental determination of

this value was based on direct measurements of the carbon dioxide and oxygen balance in a hermetically sealed system. The value obtained was 0.79 ± 0.01 with considerable dispersion (standard deviation 0.066).

The gas-exchange coefficient was found to be independent of density of the suspension within the range from 3×10^8 to 1×10^{10} cells/ml and of the intensity of photosynthesis within the range from 0.15 to 6.0 liters CO_2 /h from one liter of suspension. This level of the coefficient of gas exchange was obtained during cultivation of Chlorella on Tamiya's medium in which nitrates were the source of nitrogen.

In cases when the source of nitrogen in the medium was urea, the coefficient of gas exchange rose to 0.995 ± 0.022 . When algae were cultivated on liquid and solid products of human metabolic activity, preliminarily mineralized in an aerobic bacterial reactor, the coefficient of gas exchange moved closer to its level on nitrate media, namely to 0.82 [8]. As the results show, the coefficient of gas exchange of a Chlorella culture on mineral and mineralized organic media lies within the usual limits of the human respiratory quotient. /455

TABLE 1. Relationship between Increase in Biomass, Absorption of CO_2 and Liberation of Oxygen in Intensive Chlorella Culture

Density of suspension, g/liter	Increase in biomass, g dry weight	Absorption of CO_2 , liters/g dry weight	Liberation of O_2 , liters/g dry weight
2,2	0,19	1,00	1,23
3,75	0,28	0,97	1,11
4,5	0,41	1,03	1,20
5,6	0,29	0,97	1,21
6,75	0,42	1,04	1,24
11,2	0,32	1,03	1,11
18,0	0,46	1,04	1,38
25,7	0,47	1,02	1,36
33,0	0,60	0,98	1,23
$M \pm m$	—	$1,00 \pm 0,01$	$1,23 \pm 0,03$

Commas represent decimal points

Later, in a special series of investigations, a simultaneous study was made of the intensity of photosynthesis, the gas balance and mineral feeding of algae, and their elementary and biochemical composition. Some of these results are shown in Table 1, in which it can be seen that during the formation of 1 gram dry

substance of algae on the average 1 liter carbon dioxide is absorbed and 1.23 liters oxygen liberated (at 20°). This ratio is maintained over a fairly wide range of densities of the culture, intensities of photosynthesis, pH of the medium and intensities of illumination.

The high degree of correlation between the studied indices of intensity of photosynthesis means that any one of them is suitable as a criterion of productivity of the culture and as the source of informative signals for the automatic control of the principal growth conditions of the algal culture. Accordingly, in subsequent experiments an automatic carbon dioxide gas analyzer with positioned regulation was successfully used.

At the same time and in the same experiment the dynamics of extraction of mineral feeding elements from the culture medium and the accumulation of these elements in the algal cells (Table 2) and the biochemical composition of the cell matter were investigated [3, 6].

Comparison of loss of elements from the nutrient medium and their accumulation in the biomass shows that a proportion of them is resecreted into the culture medium, probably in the form of products of cell metabolism or destruction, /456 constituting a relatively small amount in the case of a highly productive culture.

TABLE 2. Accumulation of Principal Elements in Algal Cells

Element	In mg/g dry substance	As ratio of loss from medium, %	Element	In mg/g dry substance	As ratio of loss from medium, %
Nitrogen. . . .	80,0	96,5	Magnesium. . .	5,7	99,1
Phosphorus. . .	17,4	98,9	Iron.	0,3	—
Sulphur	11,2	—	Carbon.	500,0	92,4
Potassium . . .	16,0	—			

Commas represent decimal points.

The Chlorella biomass obtained under these conditions had an empirical formula $C_{6.6}H_{12.2}O_{3.5}N_{1.0}$ and contained: ash 7.3% of dry weight, protein 56.3%, fat 8.5%, carbohydrates including cellulose 35.2% of the organic matter.

Combustion of a substance with the formula indicated above theoretically gives a gas balance in close agreement with that obtained experimentally.

As a result of their investigations these authors obtained complex characteristics for an intensive Chlorella culture reflecting the quantitative relationship between the gas balance of the culture, the consumption of mineral feeding elements from the culture medium, their accumulation in the cells, and production of a biomass of definite composition. The results given above were obtained during

intensive cultivation conditions. This was made possible by preliminary investigation of the optimal conditions of cultivation of algae in high-density populations.

One object of the investigations was to discover the combination of conditions for cultivation of algae capable of maintaining a high level of specific productivity of their suspension. Such a combination was found and put into effect in cultivation by the film method, by means of which under laboratory conditions the productivity of the culture could be increased to 8-10 liters oxygen from one liter of suspension per hour, i.e., values commensurate with the potential capabilities of the *Chlorella* culture were obtained [7].

The achievement of such a high level of productivity was also made possible by the fact that optimal levels of the principal condition of cultivation were revised to meet the specific properties of high-density populations. In particular, experiments by G.I. Meleshko and L.M. Krasotchenko revealed higher levels of saturating concentrations of carbon dioxide than those obtained in modern laboratory practice, reaching (in air) 1.5-1.8 and 4.5-5.5% for suspension densities of $0.5-1 \times 10^9$ and $4-5 \times 10^9$ cells/ml respectively [8].

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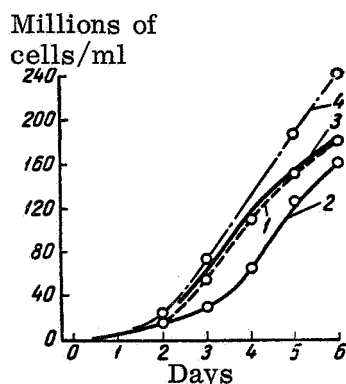


Figure 1. Growth of Culture of Algae on Freshly Prepared and Reused Medium:

- 1) Control (Freshly Prepared Medium); 2) Experiment (Reused Medium Without Dilution; 3 and 4) After Dilution 1:1 and 1:3.

When algae are cultivated in suspensions of high specific productivity, the accumulation of biologically active products in the culture medium becomes of practical importance. In some interesting experiments T.B. Galkina [2] showed that with an increase in density of the suspension, the initially stimulant action of the culture medium diminishes and then changes into an inhibitory action. The transition point in this case is the "physiological age" of this medium at which about 500 million cells will grow per milliliter irrespective of the actual cultivation time.

When the experiment was performed in reverse, serial dilutions were made of the same medium as that which exhibited an inhibitory action. This showed that the magnitude of the inhibitory effect diminishes with dilution, and with further dilution changes into a stimulant effect. These results gave conclusive evidence that the stimulants and inhibitory action of substances accumulating in the medium during prolonged cultivation of algae are of the same nature (Fig. 1).

In a series of experiments in this group of investigations the content of certain gaseous contaminants was determined in the closed air circuit of the reactor [5]. Besides concerning existing data for the liberation of carbon monoxide by the *Chlorella* culture [15, 17, 19, 20], these experiments also showed that the specific accumulation of this gas is inversely proportional to the intensity of photosynthesis in the culture (Table 3).

The results suggest that carbon monoxide formation is not directly connected with the photosynthetic process. By analogy with the formation of endogenous

carbon monoxide in the human body [20], its formation during cultivation of algae may be associated with the oxidative destruction of the tetrapyrrole ring of the chlorophyll molecule.

TABLE 3. Accumulation of Carbon Monoxide per Gram Increase in Dry Matter of *Chlorella* in Cultures of Different Productivities (Tamiya's medium)

Increase in dry substances per liter suspension, g/liter, h	Accumulation of CO, mg/g dry substance (M ± m)	Number of experiments	Increase in dry substances per liter suspension, g/liter, h	Accumulation of CO, mg/g dry substance (M ± m)	Number of experiments
0,04 (0,003 - 0,085)	2,07 ± 0,05	7	0,30 (0,170 - 0,606)	0,092 ± 0,24	7 11

Commas represent decimal points.

Parallel to this series of investigations, Ye. A. Ivanov and I. V. Aleksandrova /458 studied the dynamics and frequency characteristics of an algal suspension as an object for control [4]. By means of a low-inertia polarographic method these workers showed that a stepwise change in the intensity of illumination induces a negative (opposite) phase in the photosynthetic reaction in 97% of cases. The mean duration of this phase is 3 min, after which the intensity of photosynthesis settles down to correspond to the new level of illumination. The total duration of the transitional process is 8-12 min. A subsequent study of the relationship between the parameters of the transitional process and conditions of cultivation enabled these authors to deduce an analytical expression for transitional functions of a *Chlorella* culture depending on illumination.

These workers also showed that the use of the negative phase of the photosynthetic reaction during a stepwise change in illumination for the automatic search for the extreme value of photosynthesis and for bringing the culture away from this value can shorten the time required for this purpose by 5-6 times (to 50-60 sec) compared with a search based on the direct reaction.

The results obtained by these workers reflect the demands made by the *Chlorella* suspension on the high-speed parameters of the automatic control system based on illumination and they indicate ways of increasing the rapidity of action of automatic systems. Solution to problems of automatic control of algal cultures is inconceivable without investigation of the characteristics of self-oscillating processes in a controllable system. This problem was first considered and analyzed by Ivanov and Aleksandrova on the basis of an extensive experimental material [4] (see also the present collection). They found that spontaneous changes in photosynthesis arise fairly rarely and the probability of their appearance was 0.18. The mean value of the deviation of intensity of photosynthesis from its mean under concrete experimental conditions was ± 21% and the mean rate of deviation was 6.75%/hour. In some experiments a transition to a steady decrease /459 in intensity of photosynthesis was observed with a mean rate of 3-4%/day.

We consider that the results of such investigations, besides being of immediate importance, are also of considerable interest as general criteria for the comparative assessment of the technologic quality of methods and apparatus used for cultivation of algae.

The complex character of these investigations in high-productivity reactors made it possible to obtain extensive physiological, ecological and technological characteristics of the algal culture. These characteristics are essential both for organization of high-productivity technology and also for the algal link when simulated in isolated gas-exchange systems and closed systems of rotation of matter.

Probably these results constitute that minimal volume of information essential with respect to any object included in an ecological system. Only if such data are available for each hypothetical link in the system can we consider the possibility of planned design of experimental ecological models and also the possibility of subsequent study of complex relationship between closed systems as a fundamental task in their experimental ecology.

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BIOTECHNICAL SYSTEM OF AUTOMATIC CONTROL OF PHOTOSYNTHESIS

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Present achievements and future prospects in the field of cybernetics are such that the problem of optimal control of living systems can now be placed on the agenda for active consideration. This problem assumes its most concrete form in the field of space biology in connection with human life support during long-duration space flights.

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There is thus an urgent need for creation of a system of optimal control of living organisms in a confined space and volume, i.e., creation of a closed ecological system on the basis of the inclusion of unicellular algae, zooplankton, higher plants, animals and man as its components. This problem is most intimately connected with aspects of biocybernetics. Under natural conditions all plants are subjected to the action of 24-hour rhythms of alternating light and darkness. In response to these rhythms, similar rhythms of physiological activity have arisen in many plants. For instance, the effect of a rhythm of light and darkness on excretion of CO_2 by separate leaves has been demonstrated [10].

Preservation of rhythms in tissues of plants not subjected to periodic stimulation in the form of changes in intensity of light and temperature suggests that a clock mechanism or generator is present in the tissue itself. It is not yet clear whether these cell oscillators should be sought among individual physiological processes or whether such properties are possessed only by whole cells [10]. The external environment, the "external controlling system" directs the work of endogenous "biological clocks," and synchronization of internal and external periodic processes is not disturbed. By the creation of artificial external conditions these rhythms can be disturbed in plants for long periods of time.

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If external conditions are placed under the control of the plant, the function of a "biological clock" can be developed to a high degree by creating a strong positive link between the control system and the external "controlled system."

If constancy of optimal parameters of the external environment is maintained for a plant organism, the function of the "biological clock" loses its evolutionary significance.

It must be assumed that the plant will become adapted to such a state of the environment if, in principle, it can exist and develop without periodic changes in the external environment.

It is clearly of great interest to undertake prolonged investigations of plants from the evolutionary aspect under two conditions unusual for the organism: when the external environmental parameters are strictly constant and when they are controlled by the plant's own "controlling system." The first investigations of

this type using methods of automation and cybernetics were initiated by V. G. Karmanov and collaborators [3-5]. In these experiments a higher plant switched the light on and off without human assistance entirely in accordance with its own requirements associated with the diurnal course of transpiration.

For a bionic system of control of the source of light of this type, in principle any sensors of the intensity of photosynthesis may be used. If the electronic current at the submolecular level is a universal method of control of metabolism [9], this method is still more applicable in a biotechnical system for the control of the external parameters of the environment by a plant organism. In particular, it is rational to use an amperometric method of measuring the intensity of liberation of photosynthetic oxygen in a system for controlling the period of light and darkness by suspensions of the alga Chlorella.

The literature on this method of measurement is adequate, and the main problem in the recording technique which is discussed is the choice of measuring electrodes [11].

Measurement of the volt-ampere characteristics of individual elements in electrolytes ensures, on the one hand, adequate accuracy of measurement, and, on the other hand, it enables the mobility of certain ions to be distinguished if particular voltages are applied to the electrodes, excluding the remaining ions from the process.

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Platinum is used as the oxygen cathode for electrochemical measurement of the oxygen concentration in the liquid medium.

It was shown that if the cathode potential was between 0.6 and 0.9 V, the current in the measuring circuit was proportional to the oxygen concentration in solution [1, 12, 13]. It must be emphasized that as yet we do not completely understand electrode processes during the cathodic reduction of oxygen. However, the fact is certain that the concentration of dissolved oxygen is proportional to the current, which is negligibly small in the absence of oxygen. A detailed analysis and description of various types of oxygen cathodes of open type, oscillating and rotating cathodes, and cathodes of closed design is given in the literature [11, 13, 15, 16]. It has been shown that the smaller the electrode, the shorter the delay before it reacts to a change in oxygen concentration [13].

The Soviet literature contains a number of papers on measurement of oxygen concentration in a liquid medium in connection with biological research [2, 6-8]. In particular, in one investigation [8] an amperometric method was used to study kinetics of photosynthesis and respiration of aquatic plants on the basis of changes in the oxygen concentration in the suspension.

The advantage of the amperometric method over the polarographic method is obvious on comparing the sensitivity of measurement (10^{-9} mole/liter oxygen compared with 10^{-7}) and the speed of the electrode reaction to a change in O_2 concentration in the medium (fractions of a second compared with minutes).

To determine the intensity of photosynthesis in relative units, a platinum anode can also be used if the current in the circuit is generated by an external source.

To investigate the photoelectric characteristics of a Chlorella culture we constructed a series of measuring vessels from organic glass.

The platinum measuring electrodes inside the vessel are shown diagrammatically in Fig. 1 (lower diagram). The Chlorella suspension can flow between two cylindrical vessels through a narrow channel 20 mm long, 2 mm wide and 0.2 mm high. The floor of this channel is covered by a platinum plate measuring 12×2 mm. This platinum plate acts as recording cathode electrode of the photoelectrochemical process of photosynthesis by cells of the Chlorella suspension.

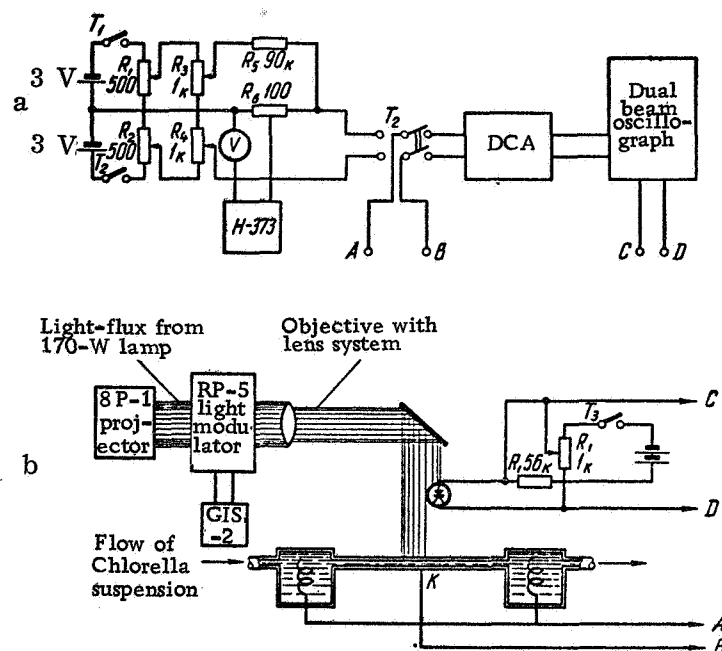


Figure 1. Diagram of System of Measurement of Intensity of Liberation of Photosynthetic Oxygen in Suspension of Chlorella Culture (a) and Construction of Electrode Measuring Cell for Automatic Impulse Control of Light Source and Fixation of Photic Impulses by Photodiode (b).

The organic glass lid, about 0.08 mm in thickness, is hermetically glued to the side walls of the canal. The second recording electrodes consist of two platinum coils wound around a vertical axis in two cylindrical vessels with an internal diameter of 15 mm and height 15 mm. To create a current of the Chlorella sus- /463
pension through the measuring electrodes and to enrich the suspension with oxygen and carbon dioxide, the two lateral cylindrical vessels are connected to two cultivators with a capacity of 250 ml each, placed at different levels.

Because of the glass edge of the cultivators, the volume of *Chlorella* suspension flowing in unit time can be regulated. A motion picture projector 8P-1 with 170 W incandescent lamp K-30 was used as source of light. The beam of light is interrupted in the narrow focus aperture of the projector by a tungsten flag measuring 2×3 mm fixed to the armature of a polarized relay RP-5. Signals from a type GIS-2 dual pulse generator or from the automatic control system depending on the index of intensity of photosynthesis can be applied to the winding of the relay to modulate the light flux.

The signal of the photoelectrochemical process of photosynthesis generated between the active cathode and the two anodes is fed into the measuring circuit (Fig. 1, top diagram). By means of commutation the signals to be investigated can be recorded by means of a dc amplifier (DCA) and dual-beam oscillograph or by means of an automatic writer of N-373 type on squared paper tape. The second channel of the oscillograph is used to record the time of application and interruption of the light flux by means of a type FD-3 photodiode. The equivalent electrical circuit of the system for measuring the intensity of photosynthesis is given in Fig. 2.

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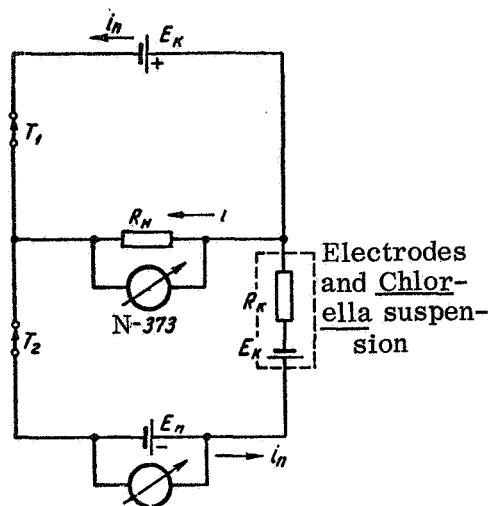


Figure 2. Equivalent Electrical Circuit of Apparatus for Measuring Intensity of Liberation of Photosynthetic O_2 by an Amperometric Method in a Suspension of *Chlorella* Culture.

The combined current of two parallel circuits produced by the EMF E_n , E_k and E_x flows through the load resistance R_H . When E_n lies between -0.6 and -0.8 , E_k represents the EMF determining the initial zero position of the pointer of the automatic writer N-373 in the absence of light flux; E_x represents the EMF on the measuring electrodes.

The fall in voltage at the resistance R_H is proportional to the current in the electrode circuit and determines the intensity of liberation of photosynthetic oxygen.

To feed the signal from the circuit for measuring the intensity of photosynthesis into the automatic control system, a differential circuit and design of the "light" and "darkness" signal detector were used in the executive organ. As signal detectors, two type FD-1 photodiodes were used, fixed on sliding contacts along an arc behind the scale of the N-373 automatic writer and inside the instrument. The photodiodes can

be moved along the arc to any scale division to the right or left with its own pointer. This movement can be carried out from the scale side without opening the instrument.

All along the axis of the moveable frame of the instrument, above the horizontal plane of the pointer is fixed a thin optical mirror, used to reflect the

beam of light through 90° , to run parallel to the line of movement of the instrument pointer until it meets the photodiode.

Depending on the direction of the current in the differential circuit of the photodiodes, the polarized relay RP-5 functions in accordance with the conventional signal "light" or "darkness." This signal is applied to the executive element, a second relay RP-5, fixed to the 8P-1 motion picture projector, where its tungsten flag on the armature obstructs or transmits the light flux to the Chlorella suspension. The whole circuit of the automatic system is supplied from a 6-V battery.

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In this way, our modified N-373 instrument, with a feedback between the Chlorella suspension and the source of light through the circuit of an amperometric system for measuring the intensity of photosynthesis, enables the light-darkness regime of the Chlorella suspension itself to be controlled automatically and at the same time enables this process to be recorded.

Clearly, if all parameters are constant, the rate of change of the intensity of photosynthesis in relative units will be determined by the sensitivity of the apparatus, i. e., by the limit of the measurement scale of the N-373 automatic writer. Consequently, by choosing the measurement scale, the recording can be made at stipulated time intervals on squared paper, to correspond to the reaching of saturation of the photosynthetic process for a stipulated volume of the colony of Chlorella culture. In this position of the automatic writer pointer, the differential circuit may operate and send a signal to the executive organ with the conventional action signal "darkness." After a definite time interval determined by the reaction of the Chlorella suspension to darkness, the curve of the recording changes to the opposite direction. The Chlorella suspension in darkness gradually modifies its function and the liberated photosynthetic oxygen is absorbed in the process of respiration. Movement of the automatic writer pointer is now determined entirely by the process of respiration of the Chlorella culture on the corresponding measurement scale of the instrument.

When it reaches the sixth position of the second photodiode, the beam of light generates a current in its circuit which operates the relay RP-5 into the conventional position of "light" and the Chlorella suspension, after a period of rest, can resume its photosynthetic function.

Having set the limit of measurement and the position of the photodiode on the automatic writer scale, on the basis of the initial velocity of photosynthesis corresponding to a definite time interval, we can bestow on the photoelectrochemical process of photosynthesis of the Chlorella culture the ability to control its own speed and, consequently, to control the times of its light and dark periods, by means of the feedback introduced between the output parameter of photosynthesis and the light flux.

This type of automatic control can be assumed to be optimal if all the other known parameters are optimal (intensity of light flux, temperature, composition of gas mixture, concentration of Chlorella suspension and composition of nutrient medium).

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Our investigations of a suspension of a culture of Chlorella pyrenoidosa 82 for a period of 6 months in a system providing automatic regulation of periods of light and darkness gave the following results.

1. For a particular volume of Chlorella culture in a particular time interval, with a particular intensity of light flux, temperature, composition of gas medium and composition of liquid nutrient medium, the feedback to the source of light reveals the required rhythm of the light and darkness regime from tracings made by the automatic writer of the intensity of photosynthesis.

2. As well as the natural rhythm of the light—darkness cycle, arrhythmia is also found, when with the onset of darkness or illumination the current in the circuit controlling the intensity of photosynthesis and the polarity of the current do not change and do not obey the external factor, but oscillate around the same level with a period of the order of 1-1.5/min, producing a drop in voltage on the load resistance (1000 Ω) of the order of 0.04 mV. The duration of the period of arrhythmia did not exceed 25 min.

Such a recording of the process investigated is illustrated in Figs. 3, a, b.

This anomalous effect cannot be ascribed to error in the working either of the automatic recording system or of the system of controlling the photoelectrochemical process of photosynthesis. On the assumption that the automatic circuit did not operate and the light flux was not interrupted, the process of increase of current must continue, because saturation of photosynthesis had not yet occurred as subsequent recordings showed.

After a temporary disturbance of the relationship between the changes in electrochemical current and the light and darkness factor of this type, the normal relationship can be restored automatically to its previous form.

It is clear from Fig. 3, c that the photoelectrochemical process in light does not reach our assigned level at which operation of the automatic change from light to darkness must take place. Chlorella suspension apparently holds off or delays the onset of periodic darkening, changes of rhythm of the process, stretching the curve recorded into an S-shape, thereby lengthening the period from 6 to 10 min.

3. Attention is drawn to the reaction time of the electrochemical current passing through the Chlorella suspension in darkness ($T_{r.d.}$) and in light ($T_{r.l.}$).

High photosynthetic function of the Chlorella suspension corresponds to the condition that $T_{r.d.}$ is greater than $T_{r.l.}$ A sign of the rapid impending onset of saturation of the photoelectrochemical process of photosynthesis is a considerable increase in the time $T_{r.l.}$ compared with $T_{r.d.}$.

In addition, the parameter itself, the time $T_{r.d.}$ decreases and this may also indicate the beginning of the process of saturation.

There is a direct relationship between the parameter $T_{r.d.}$ and the intensity of light flux and an invert relationship between the parameter $T_{r.l.}$ and the intensity of light flux.

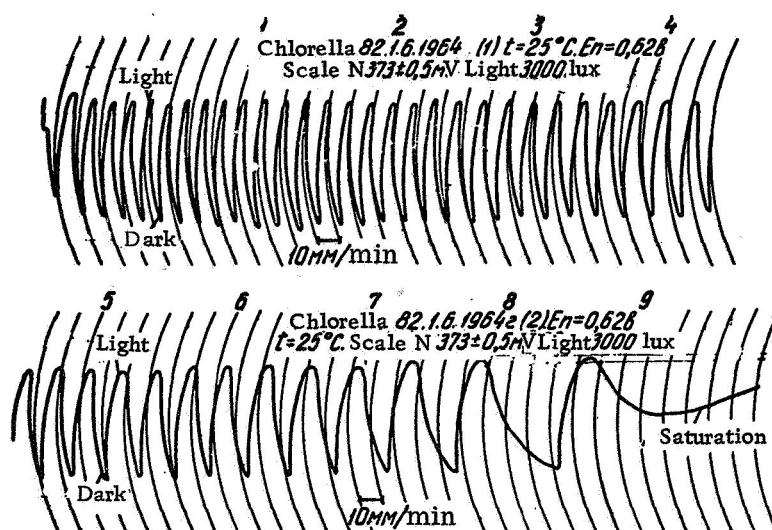


Figure 4. Recording of Photoelectrochemical Current in a Suspension of *Chlorella* Corresponding to the Process of Saturation of Photosynthesis Taking Place in a Periodic Cycle "Light—Darkness."

Figure 4 shows the beginning of a process for which only 0.3 min was required for the period light—darkness, while at the end of the recording this time is increased to 4 min and saturation of the photoelectrochemical process has taken place.

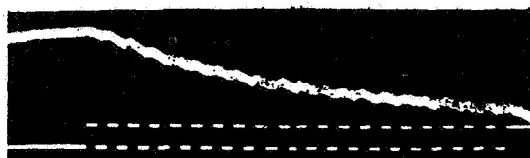


Figure 5. Stepwise Increase in Photoelectrochemical Current in *Chlorella* Suspension During Illumination with Pulses of Light of Frequency 2 Hz and Duration 0.4 sec.

As a result of electron-oscillographic investigations we were able to determine by an inertialess technique the reaction time of the electrochemical current in darkness ($T_{r.d.}$) and in light ($T_{r.l.}$) using manual control of the duration of the period of light and darkness.

Depending on the duration of the period of light and darkness, delay of the change in the current in the *Chlorella* suspension varied from 0.4 to 2 sec. With short pulses of light of frequency 2/sec and duration 0.4 sec, the reaction time is considerably shortened and the amplitude of the current greatly reduced. /469

This is in agreement with the fact that under these circumstances the photic energy adsorbed by the suspension falls considerably. The response of the photoelectrochemical current of the photosynthetic process in the *Chlorella* suspension was never observed to exceed 5 Hz when using a light source with a power of 170 W.

During prolonged illumination of the *Chlorella* suspension with light pulses at a frequency of 2 Hz and duration 0.4 sec (Fig. 5), summation of the action of photic energy on the photoelectrochemical process is observed as a stepwise curve on the oscillograms.

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STUDY OF PHOTOSYNTHESIS OF CHLORELLA GROWN UNDER CONSTANT CONDITIONS

I. V. Aleksandrova and Ye. A. Ivanov

So that photosynthesis of a Chlorella culture as used in systems of biological air regeneration can be controlled, the degree of constancy of photosynthesis must be known when growth takes place under constant conditions [1]. Several investigations have been made of this problem [2, 3], and they have shown that under constant external conditions the fluctuations in rate of photosynthesis of Chlorella vulgaris are small, but over comparatively long periods of time the intensity of photosynthesis undergoes substantial changes.

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The conditions of cultivation of Chlorella in biological air regeneration systems differ essentially from the conditions of the experiments performed by the authors cited. Because of this, we carried out an investigation to measure the "spontaneous" changes in photosynthesis of Chlorella when cultivated in a special apparatus in which certain of the conditions were maintained at what we consider to be the characteristic level of systems of biological air regeneration (Fig. 1). These conditions were: the presence of a continuous circulation of the suspension of cells in a closed system, the comparatively large volume of Chlorella suspension (7-8 liters), and the possibility of maintaining certain of the cultivation conditions constant.

To stabilize the temperature of the suspension the reactor was fitted with a jacket through which cooling water from the water supply was passed. The flow of water was controlled by the thermometer measuring the temperature of the suspension. With the constant illumination of the culture used in the experiment the error of stabilization did not exceed $\pm 0.3^\circ$.

To maintain a constant concentration of carbon dioxide and oxygen in the air bubbled through the suspension, a semiclosed gas system was used (Fig. 2). The flow rate of gas through the gas analyzer was stabilized. The batcher introduced a strictly constant dose of CO_2 into the system in unit time. The design and principle of operation of the batcher will be clear from Fig. 3. It need only be mentioned that the clock controls the valves K_1 and K_2 so that when one valve is open the other is closed.

A distinguishing feature of this system is that, besides measuring the percentage of CO_2 by volume, the gas analyzer also records the intensity of photosynthesis directly, and this greatly facilitates analysis of the experimental results.

If we denote the percentage concentration of CO_2 in the gas discharged from the system by p , the CO_2 supplied from the batcher by q , and the quantity of

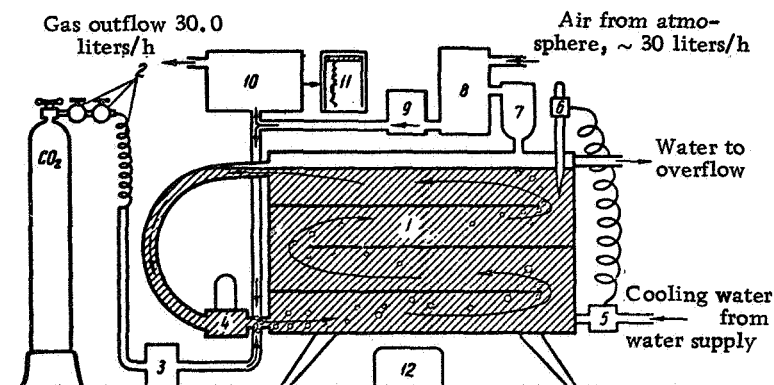


Figure 1. Diagram of Experimental Apparatus: 1) Bio-
logical Reactor; 2) Reducing Valves; 3) CO₂ Batcher; 4)
Pump; 5) Electromagnetic Valve; 6) Contact Thermome-
ter; 7) Foam Suppressor; 8) Receiver; 9) Membrane
Pump; 10) CO₂ Gas Analyzer; 11) Instrument Recording
Intensity of Photosynthesis; and 12) Voltage Stabilizer.

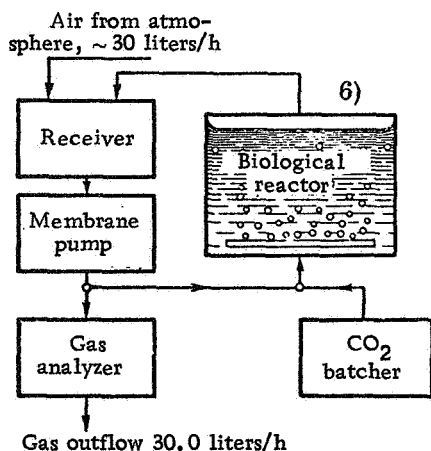


Figure 2. Diagram of Gas Sys-
tem.

gas discharged from the system by Q , we obtain an expression for the intensity of photosynthesis (I_{ps}) determined by the quantity of CO₂ assimilated by the culture in unit time, as follows:

$$I_{ps} = q - p \frac{Q}{100}.$$

It will easily be seen that if the values of q and Q are unchanged, the gas analyzer can measure the intensity of photosynthesis directly on a certain scale.

A list of the conditions of growth of the *Chlorella* as they were stabilized in the course of work with the apparatus, the level at which they were maintained, and the calculated values of the stabilization errors of these conditions and the changes produced by them in the intensity of photosynthesis are given in Table 1.

TABLE 1. Level of Photosynthesis of Chlorella under Different Conditions of Cultivation

Stabilized conditions of growth of <u>Chlorella</u>	Level of maintenance of conditions	Error of maintenance of growth conditions, %		Change in intensity of photosynthesis due to error of maintenance of growth conditions, %	
		Regular	Random	Regular	Random
Intensity of illumination of culture (type 3 N-8 incandescent lamp), lux	20000		±10		±1,33
Temperature of <u>Chlorella</u> suspension, °C	39,5		±0,3		±6,8 *
CO ₂ concentration in bubbled air, %	2,5 (By volume)	±5	±3	±1,25 **	±0,75
O ₂ concentration in bubbled air, %	22,3 (By volume)		±0,45		Small
Intensity of aeration, liters/m	10		±3		±3
Intensity of mixing of suspension (output of pump), liters/min	45		±2,5		Small
Mineral feeding	Tamiyas	-1			"
Density of culture of <u>Chlorella</u> cells, cells/cm ³	150·10 ⁶	+30	±1	-7,5 **	±0,25
Percentage of photosynthetically active cells in culture***	80		±6,25		±1,2
Concentration of Hydrogen Ions in the nutrient medium (pH value)	8,5		±6		Small
Error of apparatus measuring intensity of photosynthesis					±1

*This value also allows for the error of measurement of the conditions of solution of CO₂ in the mineral nutrient medium during changes in temperature and the associated additional change in photosynthesis.

**Regular errors in measurement of photosynthesis due to change in density of culture and to change in CO₂ concentration in bubbled air were allowed for during analysis of the experimental results.

***Cells measuring 3 and 4 μ and half the number of cells measuring 2 and 5 μ .

Commas represent decimal points.

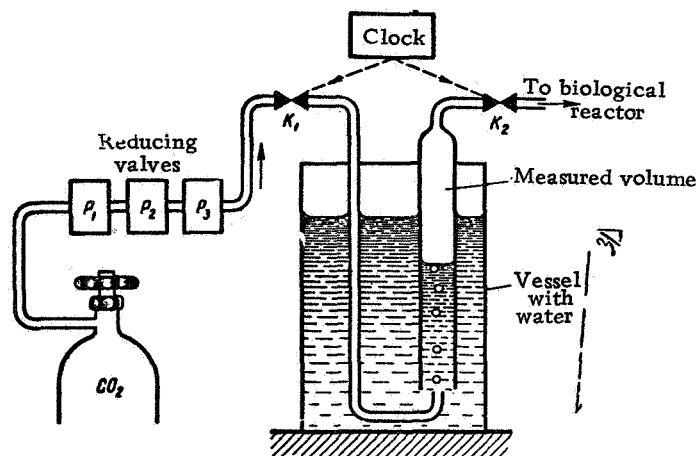


Figure 3. Diagram Showing Construction of Batcher.

The overall standard random error of measurement of photosynthesis in these experiments, calculated as the statistical mean of the random errors listed in column 7 of Table 1, was 7.75%. /472

During analysis of the experimental results, changes in the intensity of photosynthesis by a value less than this error were disregarded, but changes exceeding the error were considered as "spontaneous" changes in photosynthesis.

The curves of photosynthesis recorded by the apparatus were not smooth but contained many random fluctuations (Fig. 4). It was assumed that these fluctuations are due not to changes in photosynthesis, but to random deviations of the growth parameters from their stable values. This assumption was tested and confirmed by a series of experiments carried out on nutrient medium without seeding the culture (Fig. 5). On this basis, for the analysis of changes in photosynthesis under investigation, the curves recorded by the apparatus were first smoothed out.

The mean duration of the individual experiments was 8-10 h. Three experiments lasted 50 h each. Differences in the character of the "spontaneous" changes in photosynthesis in the longer experiments were not significant compared with the shorter. The total duration of the experiments was 320 h. Analysis of the data in the course of the experiments showed that a further increase in the number of experiments does not introduce significant changes into the mean values obtained. Accordingly, a comparatively short total duration of the experiments was all that was necessary.

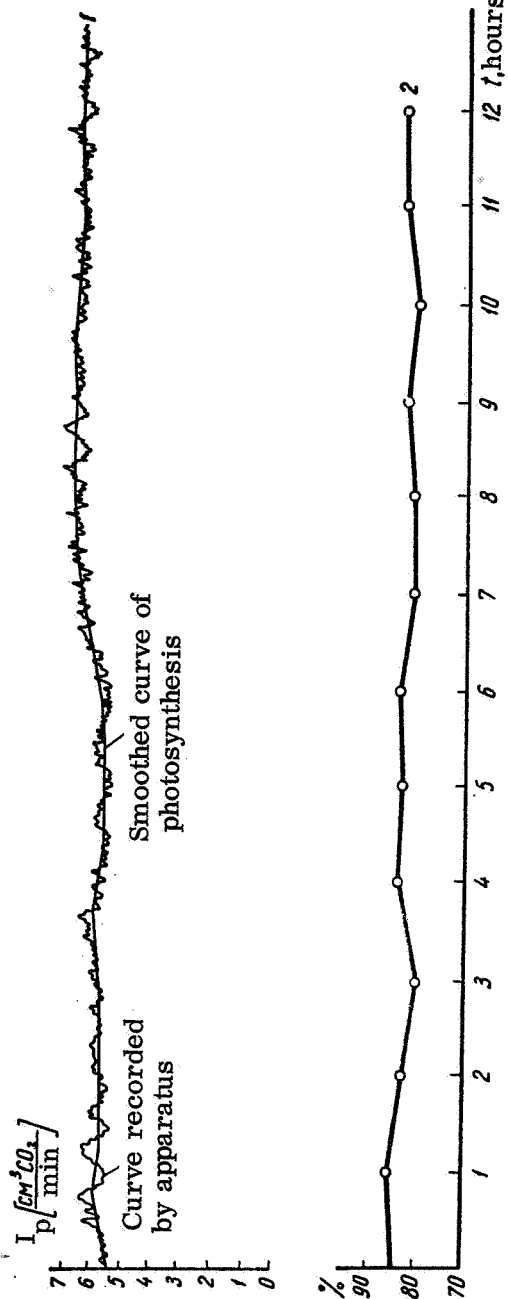


Figure 4. Example of Recording of Changes in Intensity of Photosynthesis (1) and Percentage of Photosynthetically Active Cells in a Chlorella Suspension (2) in Time.

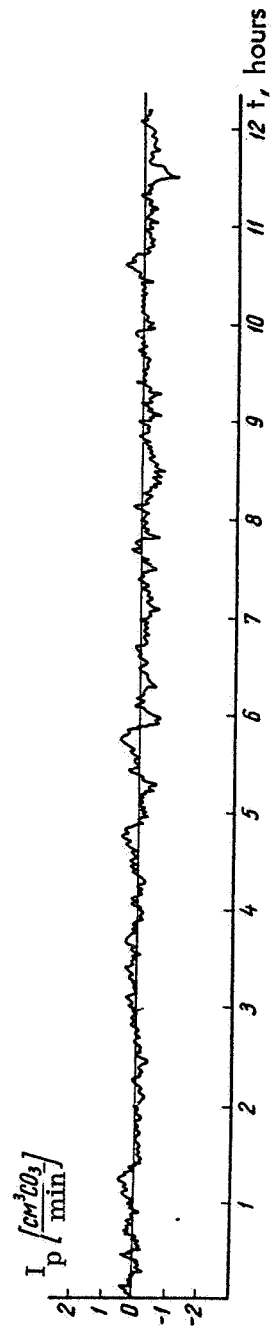


Figure 5. Recording of Intensity of Photosynthesis of Tamiya's Medium Without Seeding of Culture.

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EFFECT OF SOME GASEOUS CONTAMINANTS IN THE ATMOSPHERE ON PHOTOSYNTHETIC ACTIVITY OF CHLORELLA

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Ye. Ya. Shepelev

The system of biological regeneration of air based on photosynthesis of Chlorella is the simplest example of an ecological system with closed gas exchange. Its atmosphere is the element of the environment through which the principal interactions take place between man, algae, and certain nonliving components of the system.

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The utilization of carbon dioxide excreted by man and regeneration of oxygen, i. e., the relationship between respiratory and photosynthetic gas exchange, is not the only relationship between man and the plants, because the many-sided biochemical activity of man and plants under the conditions of a single air environment introduces a number of new, and, in particular, toxicologic problems [1, 5].

The atmosphere of a closed living space is known to contain a number of gaseous contaminants, originating from man and plants and also from various materials of the cabin itself and of its furnishings. An essential element of the investigation during the development of systems of biological air regeneration must therefore be an experimental ecological analysis of the air environment as a single medium of habitation of man and plants where each component of the atmosphere may have definite ecological significance both for each living element of the system directly and also indirectly through other elements.

The functional unity of the system of mutual provision for the gas exchange needs of man and plants requires its study as a unified system. However, this does not rule out but, on the contrary, demands a preliminary isolated analysis of the special properties of each component from the point of view of their importance to other elements of the system.

For instance, the development of photosynthetic systems of air regeneration raised the problem of the suitability of the regenerated atmosphere for respiration, because we know that plants secrete a number of substances harmful to man into the atmosphere. The experimental investigation of this problem as applied to cultivators of unicellular algae (Chlorella) revealed the practical importance of such a study and the need for further research in this direction [2].

On the other hand, we know that man is a constant source of excretion into the atmosphere of various volatile metabolic products. In particular, the dynamics of excretion of ammonia, aldehydes, carbon monoxide, ketones, hydrogen sulfide, mercaptans, hydrocarbons, fatty acids and other contaminants harmful to man and their accumulation in the inhabited atmosphere has been studied in some detail [1].

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Meanwhile some of these substances possess physiological activity with respect to metabolic processes in plants, and thus influence their photosynthetic activity. The ready solubility of many of these volatile contaminants in water makes them inevitable components of the medium in which the algae live, thus calling for investigation of the actual influence of these substances on the physiological state and photosynthetic activity of algae in the air regeneration system.

In this paper we give preliminary results showing the effect of individual anthropogenic components of the inhabited atmosphere and of a group of contaminants present in human expired air on photosynthesis of Chlorella. We studied the action of ammonia, carbon monoxide, hydrogen sulfide and acetone, and also of air expired directly by man into the gas system of the gas exchanger. The investigations were carried out in a rotation type of gas-exchange apparatus with an air volume of 25 or 65 liters and an intensity of illumination of about 26 klux. The algae (Chlorella pyrenoidosa) were cultivated on Tamiya's medium in air containing from 2 to 5% CO₂.

The scheme of the experiment was as follows: over a period of 4-6 h the rate of photosynthesis was recorded under normal conditions of cultivation on the basis of the rate of absorption of CO₂ from the air circuit of the system. A gas analyzer of "Uras" type was used for this purpose, enabling continuous automatic recording of the CO₂ concentration in the air. After a constant rate of photosynthesis had been established (control experiment), the gaseous substance to be investigated was introduced into the air circuit of the system and the rate of photosynthesis was again recorded for several hours.

The effect of addition of the test substance was calculated as the positive or negative change in velocity of photosynthesis after addition of the substance as a percentage of the initial velocity obtained in the control experiment.

During the experiment the density of the suspension usually increased within the range 700-3000 million cells/ml, corresponding to the zone of linear increase in density of the culture when grown under these conditions and in this cultivator.

The concentration of substances under study, when measured 1 h after their introduction and at the end of the experiment, varied within the following limits in different experiments: carbon monoxide from 0.1 to 0.04, ammonia from 0.04 to 0.02, acetone from 0.06 to 0.01 and hydrogen sulfide under 0.0034 mg/liter. /477

By the end of the experiment the concentration of all these substances in the air had fallen.

To study the effect of small concentrations of carbon monoxide and acetone and of expired air on the photosynthetic activity of Chlorella, five experiments were carried out in each case; in addition, three further experiments were performed to study the action of small concentrations of hydrogen sulfide and ammonia. The results obtained are given in Tables 1-5.

TABLE 1. Change in Rate of Photosynthesis of Chlorella under Influence of Low Concentrations of Ammonia

Duration of experiment, h	Ammonia concentration in air, mg/liter		Change in density of suspension during experiment, millions of cells/ml	Change in rate of CO ₂ absorption, % of control
	After 1 h	At end of experiment		
6	0,02	0,002	1845—2132	+4
18	0,02	0,002	680—1394	+9
17	0,03	Traces	720—1216	+14

Commas represent decimal points.

As Table 1 shows, in the last two experiments a slight stimulant effect was observed, due to absorption of a considerable part of the ammonia from the gaseous phase. There is no justification for regarding this effect as to any degree specific. Under the conditions of these experiments, ammonia has no direct action on Chlorella cells, because it is combined in the culture medium in the form of ammonium carbonate, used by algae as a source of nitrogen.

TABLE 2. Changes in Rate of Photosynthesis of Chlorella under Influence of Low Concentrations of Carbon Monoxide

Duration of experiment, h	CO concentration in air, mg/liter		Change in density of suspension during experiment, millions of cells/ml	Change in rate of CO ₂ absorption, % of control
	After 1 h	At end of experiment		
12	0,107	0,02	826—1428	+17
5	0,036	0,015	2500—2950	+53
8	0,100	0,047	984—1806	+41
9	0,003	Traces	970—2226	+24
4	0,09	0,04	1611—1956	+19

Commas represent decimal points.

These results are of course insufficient to allow definite conclusions to be drawn, but to some extent they agree with the findings of V. V. Pinevich and

co-workers [3] indicating that Chlorella utilizes ammoniacal forms of nitrogen in preference to other sources of nitrogen feeding.

Data showing the effect of small doses of carbon monoxide are given in Table 2.

It is clear from Table 2 that after introduction of carbon monoxide into the gas exchanger the mean CO_2 utilization by the Chlorella cells increased in every case by between 17 and 53%. A similar effect was observed in experiments to study the action of acetone (Table 3).

TABLE 3. Changes in Rate of Photosynthesis of Chlorella under Influences of Small Concentrations of Acetone

Duration of experiment, h	Acetone concentration in air after 10 min, mg/liter	Change in density of suspension during experiment, millions of cells/ml	Change in rate of CO_2 absorption % of control
2	0,02	1050—1102	+24
3	0,005	2300—2417	+18
3	0,06	3100—3341	+11
2	0,016	800—890	+ 4
5	0,005	2300—2625	+16

Commas represent decimal points.

marked inhibitory action, in full agreement with its blocking properties toward enzyme systems containing heavy metals [4].

Of the five experiments with expired air, three (Nos. 2, 3 and 5) gave some evidence of slight inhibition of photosynthesis (Table 5).

A noticeable feature in the experiments with expired air was that in none of them was a stimulant effect obtained, as was nearly always observed in our other investigations (G.I. Meleshko) in which the air medium for Chlorella was the air from an inhabited airtight cabin containing not only expired air, but also the whole range of gaseous contaminants excreted as a result of human metabolic activity.

The results of this investigation clearly do not yet justify final conclusions, and one of its purposes is to draw the attention of investigators to this problem.

It follows from the results in Table 3 that the character of the changes in the rate of photosynthesis under the influence of acetone was similar to that observed during the action of carbon monoxide, but the intensity of the stimulant effect was significantly smaller in this case. The maximal increase in the rate of CO_2 absorption by the cells here was 24%.

The results of experiments to study the action of hydrogen sulfide are given in Table 4.

The results in Table 4 show that in two experiments with a higher concentration of hydrogen sulfide it had a

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TABLE 4. Changes in Rate of Photosynthesis of Chlorella under Influence of Small Concentrations of Hydrogen Sulfide

Duration of experiment, h	Hydrogen sulfide concentration in air, mg/liter	Changes in density of suspension during experiment, millions of cells/ml	Change in rate of CO ₂ absorption, % of control
	Less than 0,0001	1140—1785	—4
7	0,0034	1550—1894	—44
5	0,0025	1250—1897	—22

Commas represent decimal points.

TABLE 5. Changes in Rate of Photosynthesis of Chlorella under Influence of Human Expired Air

Duration of experiment, h	Change in density of suspension during experiment, millions of cells/ml	Change in rate of CO ₂ absorption, % of control	Duration of experiment, h	Change in density of suspension during experiment, millions of cells/ml	Change in rate of CO ₂ absorption, % of control
6	940—1228	—2	3	1700—1920	—6
4	900—1168	—12	11	1080—2052	—19
2	1300—1407	—20			

This work is merely a preliminary attempt to establish the phenomenologic aspect of the situation insofar as it concerns concentrations of certain gaseous contaminants actually found in the inhabited atmosphere. However, in the first stages of the investigations, even the purely phenomenologic approach can prove useful. In particular, for instance, subsequent confirmation of the results obtained in this investigation concerning the absorption of carbon monoxide, ammonia and acetone from regenerated air by Chlorella cells, with a distinctly positive effect on photosynthesis, would be grounds for reexamining the question of the need for special filters to absorb these substances when present in photosynthetic systems.

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We consider that the study of the problems discussed in this paper must in the future form a permanent component of experimental ecological investigations of animal-plant associations.

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CHARACTERISTICS OF GROWTH AND GAS EXCHANGE OF THE ALGA ANACYSTIS NIDULANS IN INTENSIVE CULTURE

T. B. Galkina, I. I. Kashkovskiy, O. A. Kurapova, Ye. K. Lebedeva, G. I. Meleshko and Yu. N. Ul'yanin

When the choice of photoautotrophic organisms is being made for life support systems, the main requirement is high intensity of their photosynthetic processes and resistance to various external environmental factors. /480

The blue-green algae are of considerable interest from this point of view. As the most primitive photoautotrophic organisms, the blue-green algae exhibit unusual physiological and biochemical variety connected with the great plasticity of their organization. This enables the blue-green algae to live under extreme conditions [2, 7] and thus provides a wide range of forms possessing the most useful physiological and ecological characteristics.

Contrary to widespread views, the literature now contains many facts indicating the high physiological activity of certain known forms of blue-green algae [8, 10].

One such form is Anacystis nidulans. When under conditions of intensive movement this unicellular alga is shaped like a short cylinder or rod measuring $1.3 \pm 0.2 \times 2.5 \pm 0.2 \mu$. This form of alga was generously presented to us by V. V. Pinevich (Biological Institute, Leningrad University). /481

The object of the present investigation was to continue the search for new forms of algae for use in photosynthetic gas exchanges. We investigated the productivity of this culture when grown under intensive conditions, the characteristics of its gas exchange, and the chemical composition of accumulated organic matter.

The culture of A. nidulans was grown on Arnon's medium. This medium was recommended to us by the Leningrad Biological Institute. After comparative studies of the rate of growth of a culture on the media of Arnon, Kratz and Myers [10], and Takha [6], used for cultivation of blue-green algae, Arnon's medium was found to be most suitable for intensive cultivation of the algae because of its high concentration of mineral elements.

The composition of this medium was as follows (in g/liter): KNO_3 2.02; K_2HPO_4 0.35; MgSO_4 0.25; KCl 0.3; NaCl 0.12; FeSO_4 0.025; CaSO_4 0.09; EDTA 0.05. Trace elements were added at the rate of 1 ml/liter medium.

Before the experiment the culture was grown in a luminostat until its density was 0.2-0.5 g/liter, with an intensity of illumination of 7-8 klux and at a

temperature of 37–40°, ventilated with a mixture of air and carbon dioxide. The culture was then centrifuged at 5000 rpm and resuspended in fresh nutrient medium with a single or double concentration of elements, after which the suspension was transferred into the experimental reactor.

The reactor consisted of a rotating cylinder with its outer surface illuminated by 3N-8 incandescent lamps. The intensity of illumination in the experiments varied from 20 to 60 klux depending on the density of the suspension. The experimental system included a closed air circuit with a volume of 75 liters, in which the circulation of air was produced by a membrane pump. The CO₂ concentration in the air circuit of the system was maintained between 1 and 5%. In these experiments the main conditions of cultivation, which had previously found to be optimal for *Chlorella* when grown in the same reactor were maintained. The air circuit of the system also included an automatic recording gas analyzer (Uras) for measuring the CO₂ concentration in the gaseous phase of the system. The CO₂ and oxygen concentration were periodically checked with Haldane's apparatus. The quantity of CO₂ dissolved and fixed in the suspension was determined with Van Slyke's apparatus and the pH of the suspension was measured potentiometrically.

The intensity of photosynthesis of the algal culture was assessed by the rate of CO₂ consumption, the rate of O₂ liberation, and the rate of accumulation of biomass. The increase in biomass was determined from the dry weight of the centrifuged and washed mass of cells. The elementary composition of the dry material was determined by chemical analysis. Ash was also determined quantitatively and qualitatively. In the course of the experiment the nitrogen concentration in the medium was checked.

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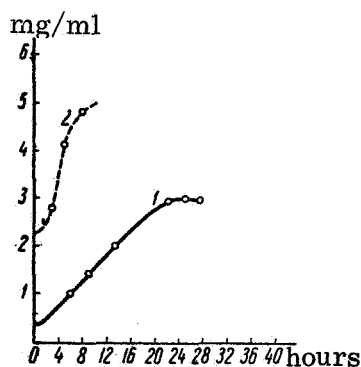


Figure 1. Dynamics of Growth of *A. nidulans* in Intensive Culture with Initial Density 0.35 (1) and 2.2 (2) mg/ml.

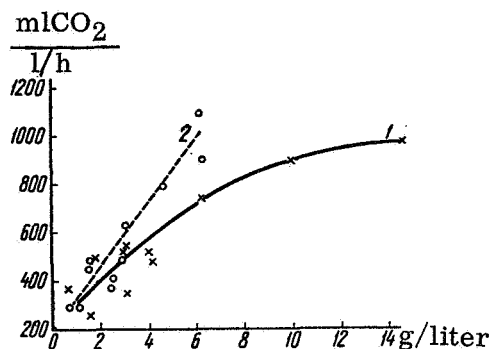


Figure 2. Comparative Characteristics of Rate of CO₂ Absorption in Suspensions of *Chlorella* (1) and *Anacystis* (2).

The characteristics of the rate of growth of the culture are illustrated in Fig. 1. Curve 2 shows that with a fairly high initial density the rate of increase

of biomass over the linear portion of the curve is 0.65 g dry substance/liter/h, close to the productivity of the most active thermophilic forms of Chlorella cultivated under the same conditions.

The rates of absorption of CO₂ by Anacystis cultures of different densities are shown in Fig. 2 (Curve 2). For comparison, the corresponding values for Chlorella pyrenoidosa S-39 obtained with analogous conditions of cultivation in the same reactor [4] are given (Curve 1).

It is clear from Fig. 2 that with suspensions of density of the order of 1-3 g/liter, the productivity per unit volume of suspension of the compared forms of algae is practically identical.

With a greater density of the suspension (6-7 g/liter) and a corresponding increase in illumination, the productivity of the Anacystis suspension per liter was found to be higher than that of Chlorella.

This should not be taken to mean that the absolute productivity of Anacystis is greater, because for equal densities by weight, the Chlorella suspension contains fewer cells. However, the smaller size of the Anacystis cells may be another advantage, because intensity of metabolism is proportional to total surface area of the cells.

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Hence, like Chlorella, Anacystis can maintain a forced cultivation regime. Its productivity during preliminary trials under these conditions reached 26 liters CO₂ per liter suspension per day.

The relationship between the quantity of CO₂ absorbed by the cells and the quantity of oxygen liberated was also studied in these experiments. The results are given in Table 1.

TABLE 1. Relationship between CO₂ Absorbed and O₂ Liberated during Intensive Cultivation of A. nidulans

Volume of CO ₂ absorbed, liters	Volume of oxygen liberated, liters	CO ₂ /O ₂	Volume of CO ₂ absorbed, liters	Volume of oxygen liberated, liters	CO ₂ /O ₂
0,785	1,125	0,70	0,820	1,120	0,73
0,825	0,975	0,84	0,150	0,220	0,67
0,900	1,200	0,75	0,510	0,675	0,72
2,850	3,970	0,72	0,525	0,825	0,90
1,010	1,350	0,75	1,050	1,350	0,78
1,200	1,420	0,84	1,200	1,420	0,84
2,620	2,850	0,92	2,250	2,550	0,88
0,450	0,600	0,75	2,550	2,850	0,89
Mean			0,79		

Commas represent decimal points.

The results given in Table 1 show that the CO_2/O_2 ratio (the accumulation coefficient) varies from 0.70 to 0.90, with a mean value of 0.79. The effect of the nitrogen food supply on fluctuations in the assimilation coefficient of *Anacystis* is worth noting. After complete exhaustion of nitrate nitrogen from the medium (the appearance of NO_2^- or NH_4^+ ions in the medium was not observed during cultivation), growth of the culture continued without any appreciable decrease in rate (Fig. 3). The process of depletion of nitrogen in the medium, when calculated per gram of biomass formed, shows considerable irregularity in the case of *Anacystis* in contrast to *Chlorella* and *Scenedesmus*. As an example, data for nitrogen depletion in the medium are given in Table 2.

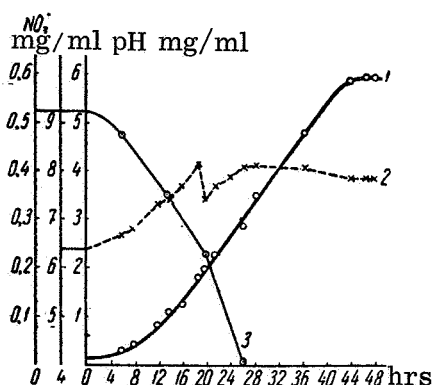


Figure 3. Dynamics of Increase of Biomass (1), pH of Medium (2) and Depletion of Nitrogen in Medium and (3) in a Culture of *Anacystis*.

Chlorella. The quantity of nitrogen found in the dry substance of the cells is the same as its mean extraction from the medium when the cultivation curve becomes a plateau. The utilization of extremely large quantities of nitrogen in the initial periods of growth and maintenance of a high rate of growth of the culture when mineral nitrogen is absent from the medium reflect distinctive features of the cell metabolism of blue-green algae. There are reports in the literature that the cells of these algae accumulate large quantities of soluble organic forms of nitrogen, foremost among which are diamino acids and amides [1, 11].

The dynamics of the pH of the suspension during cultivation of *Anacystis* is also shown in Fig. 3. With an increase in the biomass the pH moved toward the alkaline side from 5.3 to 7.9 in single-strength medium and from 4.5 to 8.1 in double-strength. The change in pH over this range was not reflected in the rate of growth of the culture. The increase in pH of the suspension was accompanied by accumulation of fixed CO_2 to 0.6 - 0.7 cm^3/ml . Near the time when all

NO_3^- ions had disappeared from the medium the pH and concentration of bicarbonates in the suspension were stabilized at the same level.

Usually a steep drop is observed in nitrogen depletion in most cases during the first hours of the experiment, and sometimes in the middle of the experiment. As a rule this drop is followed by a decrease in the consumption of nitrogen from the medium by the cells.

The mean loss of nitrogen from the medium, calculated per gram of dry substance at the moment of its total disappearance from the medium was fairly stable, amounting to 120-150 mg/g depending on its initial concentration in the medium. If the loss of nitrogen from the medium is related to the total increase of biomass before the curve flattens out on the plateau, a value for the relative loss of nitrogen of 70-90 mg/g dry substance is obtained, which is very close to the extraction of nitrogen by

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TABLE 2. Rate of Increase of Biomass and Extraction of Nitrogen from Medium during Intensive Cultivation of *A. nidulans*

Time, h	Density of suspension, g/liter	Nitrogen concentration, mg/liter	Extraction of nitrogen, mg/g biomass	Time, h	Density of suspension, g/liter	Nitrogen concentration, mg/liter	Extraction of nitrogen, mg/g biomass
Single strength Arnon's medium				Double strength Arnon's medium			
0	0,25	300	—	0	0,15	525	—
4	0,40	272	182	8	0,45	460	216
8	0,84	230	95	12	0,81	390	195
12	1,44	166	151	16	1,35	305	120
16	2,04	66	166	20	2,05	220	121
20	2,64	8	97	24	2,75	110	143
24	2,76	0	66	28	3,50	0	133
During 21 h	2,80	0	117	During 28 h	3,50	0	156

Commas represent decimal points.

TABLE 3. Elementary Chemical Composition of Biomass of *A. nidulans* (% of dry weight)

Experiment No.	N	P	Na	K	Ca	Mg	Fe
1	6,82	0,77	0,05	0,03	0,15	0,24	0,14
2	8,00	1,20	0,04	0,07	0,26	0,40	0,09
3	8,62	0,96	0,04	0,05	0,25	0,25	0,08
4	8,19	1,40	0,04	0,03	0,13	0,30	0,08
5	8,00	1,10	0,04	0,06	0,21	0,24	0,06
6	7,91	1,43	0,03	0,04	0,18	0,30	0,09
Mean	7,92	1,13	0,04	0,05	0,20	0,29	0,09

Commas represent decimal points.

It was also interesting to determine the elementary composition of the organic matter of the cells, to some extent characteristic of their biochemical composition.

For this purpose a washed and dried biomass obtained from experiments when the growth curve had come out onto a plateau was used. The ash content constituting on the average 4.6% of the dry weight, and its composition were determined in the biomass (Table 3).

The carbon content in the organic matter, expressed as a proportion of the ash-free residue, was 51.44%, the hydrogen content 7.39%, nitrogen 8.30% and oxygen 32.87% (mean results of fixed determinations).

Using these data as a starting point, the empirical formula of the organic matter of which the cells of A. nidulans are formed was calculated, the result being $C_{7.22}H_{12.40}O_{3.46}N$.

The reducing power of the organic matter (R), calculated by means of Milner's equation [12], is 40.81. This value is rather higher than for Chlorella [5].

These results show that in its elementary chemical composition the biomass of Anacystis is similar to that of Chlorella, from which it differs mainly in its lower content of monovalent cations K and Na [3]. The content of the principal biogenic element, carbon, hydrogen, oxygen and nitrogen, expressed relative to the content of organic matter, likewise showed no significant difference from their content in Chlorella. /486

The results of these investigations showed that Anacystis nidulans can be used in intensive cultivation as well as Chlorella. A further study of the nitrogen feeding requirement and the associated metabolic processes in the cell may reveal the possibility of controlling the assimilation coefficient and hence the composition of the biomass of this alga.

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CHOICE OF ANIMAL COMPONENTS OF CLOSED ECOLOGICAL SYSTEMS

N. V. Mironova

As components of closed ecological systems various authors [1, 5, 9, 10] have suggested crustaceans, mollusks, fishes, hens, rabbits and goats. /486

During the study of the provision of a balanced human diet during long space flights the question of incorporation of vertebrates in the food cycles naturally arises, for this would provide man with essential and first-class proteins, fats and other food substances and, at the same time, give a diet to which he is accustomed.

There are few reports in the literature dealing with the inclusion of fish in a closed ecological system [14].

As components of a closed ecological system under spacecraft conditions fishes possess many advantages. They can be used almost entirely as food, because their body does not contain indigestible keratinous or chitinous parts. Fish also have very high food value and very acceptable taste properties. /487

For these reasons the possibility must be examined that among fishes species can be chosen which are capable of existing and propagating in small containers under stipulated temperature conditions (a wide range being desirable), and not too fastidious with respect to oxygen content and other qualities of the water (pollution, pH, etc.).

Finally, a most important condition is the possibility that the selected species can be introduced between preceding and succeeding links in the food chain, i. e., the ability of this species to utilize organic matter of mainly vegetable origin, unsuitable as human food (unicellular algae, green mass of higher plants), on the one hand, and its suitability as human food on the other hand.

The next stage in the study of this problem must be to establish quantitative indices for consumption and production; to study the ability of the species to give a rapid, considerable and uniform increase in biomass from a unit volume and unit weight of food. After preliminary choice of test object on the basis of general data concerning the biology of the species, the primary research program can be planned as follows:

- 1) The study of the limits of food adaptability of the chosen object, its ability to utilize green mass of lower and higher plants and to grow on such a diet;
- 2) The study of quantitative food requirements depending on its composition and the age of the investigated organisms;
- 3) The study of the rate of its increase in weight;

4) The study of special features and rate of reproduction;

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5) The obtaining of data for the rate of increase of population and of the total biomass of the population.

The difficulty in choosing an object satisfying all the demands made on components of a closed ecological system will be obvious. For this reason, several species must be investigated.

At the present time the species corresponding most fully to the presented demands is the tropical fish known as the tilapia (Tilapia mossambica Peters) belonging to the Cichlidae family. This conclusion is based on the following properties of this species:

1. High ecological plasticity.
2. Omnivorous and mainly phytophagous feeding habits. Ability to feed on algae, green mass of higher plants, and animals.
3. A supposed ability to feed on Chlorella.
4. A technically convenient optimum temperature of existence of between 20 and 28°, not requiring special thermoregulatory devices for its maintenance.
5. Resistance to changes in temperature over a wide range (from +8 - 10° to nearly 40°).
6. Absence of demand of seasonal changes in temperature conditions.
7. Absence of seasonal cyclic pattern of growth and reproduction (with consequent regular increase in biomass).
8. Early maturation, frequent spawning all the year round, caring for offspring, rapid increase in population of biomass.
9. High rate of growth at an early age and attainment of suitable dimensions for consumption as food within a few months.
10. Ability to exist in a high stocking density without appreciable influence on growth and propagation, reported in the literature [12].

From the properties of Tilapia mossambica Peters listed above, it appears likely that a uniform increase in proteins may be obtained throughout the year by keeping this species under constant conditions of existence.

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It must be added to these remarks that analysis of the relative weights of different parts of the tilapia body (Table 1) showed that even in tilapia fry the weight of meat and skin as a percentage of the live body weight is very similar to that of the carp, amur, silver carp and bighead.

TABLE 1. Relative Weights of Various Parts of the Body of Fishes (in % of Live Weight)*

Species	Sex	Number of specimens	Weight of fish, in g	Head	Viscera	Fins and bones	Meat and skin	Scales	Total	Loss of blood and moisture	Remarks
Tilapia. . . .	♂	1	130,35	19,64	11,43	17,72	43,54	3,49	95,82	4,18	Dissected
"	♂	1	62,9	18,84	8,82	16,38	46,02	4,06	94,12	5,88	raw fishes
"	♀	1	126,2	18,34	4,91	9,51	52,02	4,52	89,30	10,70	Dissected
"	♀	1	66,85	18,48	6,73	10,92	49,53	4,26	89,98	10,02	cooked fishes
"	juv	5	18,7	20,05	8,13	11,76	53,48		93,42	6,58	"
Carp.	?	?	428	16,9	12,1	14,1	52,4	4,5	100,0	—	According to
White amur.	?	?	794	13,4	9,4	12,4	61,2	3,6	100,0	—	Sukhoverkhov [4]
Silver carp	?	?	449	17,0	10,6	12,4	55,6	4,4	100,0	—	"
Big head. . .	?	?	703	23,2	7,6	14,6	51,1	3,5	100,0	—	"

*The weight of blood and moisture lost during dissection is not distinguished in the data cited from the literature. In our results they are shown in a separate column. If this amount is added to the weight of meat, the results obtained are identical to those characteristic of the carp, while amur, silver carp and bighead.

Commas represent decimal points.

CONDITIONS OF EXISTENCE OF EXPERIMENTAL FISH

Special experiments to determine the tolerance limits of tilapia to temperature and content of oxygen and organic substances in water were not undertaken. However, the water temperature in the aquaria was recorded twice a day; in addition, samples of water from aquaria with different densities of stocking were analyzed hydrochemically, in the morning before cleaning the aquaria (at the moment of worst pollution of the water by decomposition products of excreta) and at the end of the day (after changing the water and introduction of food into the aquaria). The fluctuations in temperature and chemical properties of the water thus discovered to some extent indicate changes in external environmental factors tolerated by tilapia (Table 2).

TABLE 2. Fluctuations in Conditions of Existence of Tilapia in Experimental Aquaria*

Indices	Minimum	Maximum
Water temperature.	17,9	37,6
Mean water temperature for the month	20,7	27,3
Fluctuations in water temperature during month.	1,0	17,5
Fluctuations in water temperature during day	0,0	17,5
pH.	<6,0	6,8
Oxygen concentration in water, mg/liter.	0,85	8,37
Oxygen saturation of water, %.	9,6	94,5
B. O. D. (permanganate)	11,8	17,3
B. O. D. (bichromate)	23,2	67,2

*The hydrochemical analyses were performed by N. F. Smirnova, Hydrochemist in the Laboratory of Freshwater and Experimental Hydrobiology, AIN, USSR Academy of Sciences.

Commas represent decimal points.

A factor limiting the distribution of tilapia, including *Tilapia mossambica* under natural conditions is the winter water temperature [13]. A temperature of 8° is lethal for this species [6, 12].

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As the results in Table 2 show, in our experiment the tilapia lived in a mean temperature of 20.7-27.3°. However, in some aquaria without special heating of the water, at certain periods the temperature fell to 17.9°; in some cases it rose for a short time to 30, 34 and 37.6°. As a rule the diurnal fluctuations of temperature did not exceed 2-3°.

The oxygen concentration in the water was comparatively small, varying in different aquaria from 0.85 to 8.37 mg/liter, and the percentage saturation varied from 9.6 to 94.5. In half the cases mentioned the oxygen concentration in the water was below 2 mg/liter and the percentage saturation was below 50, while in one-third of cases it was below 20. The fish were kept in aquaria made of organic glass, 40 liters in capacity excluding soil and plants.

The limits of stocking density were not studied. Up to 200 specimens of 2-month-old fry and up to 70 specimens of 10- to 12-months-old fish were kept in the

aquaria. The maximal total live weight of fish per 40 liters water was 1408 g, i. e., 35.2 g/liter water.

NUTRITION

According to reports in the literature, Tilapia mossambica is extremely accommodating as regards food and under natural conditions will eat both animal and plant food. It lives on phytoplankton, filamentous algae, green mass of algae and higher aquatic plants, zooplankton, worms, insects and their larvae, tiny shrimps and other crustaceans [7, 12]. In aquaria and ponds it readily eats white bread, chopped meat and fish, mollusks, oat flakes, oat and corn flour, all types of scraps and oil cake, grain, rice, beans, soybeans, pressed coconut, green mass of various plants, and kitchen waste.

In 1963 we carried out investigations to study the ability of tilapia to feed on green particles of higher land plants of different families and differences in their increase in weight when fed in this way by comparison with fish receiving animal food (mainly moths).

Initially all the tilapias received food usually given the fish in aquaria—midge larvae, tubifex, living and, in very small amounts dried, water fleas. Fry obtained in the laboratory were fed on infusorians, vinegar eelworms, and water fleas, followed by small tubifex, larger tubifex, cut-up midge larvae and, finally, intact and large midge larvae. In 1964 the fry were given a simpler diet. In the early stages (until one month) the young fish received vinegar eelworms and after the 1st-14th day, ground midge larvae together with ground sorrel after the 10th-20th day. Later, they received cut-up, followed by whole midge larvae or unchopped green matter. In addition, the larvae and young fish received Chlorella as a suspension of living cells. The fact that the larvae ate the Chlorella cells was proved by examination of the excreta and intestinal contents, but it is of course impossible to estimate this consumption quantitatively and, still less, to observe it directly. /491

Some of the experimental fish were used to study their ability to eat plant food, to determine which plants were preserved and which were rejected, and to make observations on changes in the rate of growth on such a diet. For a period of 6 months (from the age of 8 to 14 months) these fishes received a varied diet in which the proportion of animal food was gradually reduced and the proportion of plant food increased. After 70 days, animal food was completely excluded from the diet. In two aquaria no midge larvae whatever were given for 113 days.

During the experiment the ability of tilapias to eat 12 species of plants belonging to the families Polygonaceae, Chenopodiaceae, Umbelliferae, Caryophyllaceae, Cruciferae and Cucurbitaceae was investigated. The fish were given green leaves of sorrel, rhubarb, beetroot, two species of orache, carrot, chickweed, cabbage, cauliflower, radish, lettuce and vegetable marrow. All these plants were eaten completely by the fish, but not with the same avidity. Sorrel and rhubarb were eaten with preference, and carrot leaves least avidly. The harder and more solid parts of plants were eaten badly (the stems, the leaf veins). In an analogous experiment, Bishai [8] kept tilapia on Leguminaceae (Vicia faba L.).

TABLE 3. 24-Hour Index for Tilapias of Different Ages

Aquarium No.	Age, months									
	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12
1L ₅	25	18	11	11	6,0	5,5	5,7	4,4	3,4	2,9
2L ₅	26	16	10	9	6,8	5,6	5,7	4,9	3,8	3,5
L ₁₀	11	18	12	11	6,4	5,0	5,0	3,6	3,5	3,6
L _{5a}	25	22	11	5,0	5,0	4,5	3,6	4,0	3,3	2,7
L _{10a}	24	18	10	6,0	—	4,2	5,5	4,9	3,6	3,5
Mean	22,2	18,4	10,8	8,4	6,0	4,9	5,1	4,3	3,5	3,2

Commas represent decimal points.

Because all the plants suggested without exception were eaten, it can be hoped that tilapia will prove capable of being fed on the green mass of plants which will be included as components of the closed ecological system.

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The food given to the fish was analyzed quantitatively starting from the time when they reach the age of about 1 month. Before this age the larvae and young fish were fed on infusorians and vinegar eelworms, which cannot be analyzed gravimetrically.

By weighing the fish every month, the quantity of food required per unit body weight of tilapias of different ages per day can be calculated (as a mean value per month). This quantity, expressed as a percentage, is known as the 24-hour index. Data for the 24-hour index for tilapias of different ages and on different diets are given in Table 3. As this table shows, the 24-hour index for tilapia decreases with age. If animal food is given, the 24-hour index between the ages of 2 and 3 months is 22, between 3 and 4 months 18, from 5 to 6 months its value has fallen to 8, and after 9 months it does not exceed 5. If tilapias aged 10-13 months are fed on plant food only, the 24-hour index varies between 10 and 20.

The mean monthly food indices, expressing the ratio between the weight of food eaten and the increase in body weight of the fish, are given in Table 4. The food index for fish aged 2-3 months fed on an animal diet varies from 2.8 to 10.1 with a mean value of 6.5. This means that for every 6.5 g of food eaten, the fish gains 1 g body weight. The food index for the fish aged 9 months has a mean value of 10.

If the fish are transferred to a plant diet, consisting of plants to which they are unaccustomed, the food index rises appreciably. For fish (aged from 10 to 13 months) receiving a plant diet exclusively, the mean food index varied from 58 to 92. Much better indices of food utilization relative to growth were obtained for fish receiving mixed diet, in which various plants were supplemented by from 20 to 60% of midge larvae. The food index for these fish varied from 58 to 27 respectively.

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TABLE 4. Food Index of Tilapias of Different Ages

Aquarium No.	Age, months									
	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12
1L ₅	6,8	7,4	8,9	8,8	6,0	8,4	6,2	10,5	19,5	12,0
2L ₅	7,6	8,5	10,6	10,7	5,6	6,8	8,4	10,3	16,4	10,0
L ₁₀	2,8	8,6	7,4	12,8	5,9	7,1	9,9	9,4	23,6	9,5
L _{5a}	5,2	7,2	8,7	6,5	6,7	8,3	10,7	10,9	11,0	12,8
L _{10a}	10,1	8,2	8,0	6,0		7,9	—	11,0	11,3	10,4
Mean	6,5	8,0	8,7	8,9	6,0	7,7	8,8	10,4	16,3	10,9

Commas represent decimal points.

GROWTH

All the experimental fishes starting from the age of 2 months were measured and weighed every month. In this way data were obtained for their mean length, mean weight and increase in these parameters for each month of life.

Before describing the results showing the rate of growth in weight of the tilapias in the aquaria, it should be emphasized that the gain in weight and size cannot in any way be regarded as the maximum possible. In the series of experiments undertaken, no attempt was made to obtain maximum increase by the use of complex diets and by increasing the qualitative value of the diet. On the contrary, the fish were deliberately kept under unfavorable nutritional conditions in order to determine their tolerance, and their adaptability and potential ability to grow when fed on a monotonous diet quite out of keeping with natural conditions. Subsequent investigations will be carried out to investigate ways of keeping and feeding tilapias in order to obtain the maximum increase in weight.

In his monograph on the biology and cultivation of tilapia, Chimitz [11, 12] cites the following limiting dimensions and weight of *T. mossambica*: 38-39 cm and 700-850 g. There are also reports that individuals of this species have attained even larger sizes.

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In connection with the present problem, the weight and rate of growth of the fry are interesting, because the long-term rearing of fish during space flights may not be economic. It is therefore important to know as far as possible ahead when the fish will reach a size suitable for use as food.

Data showing the gain in weight of tilapias for each month of life during the first year as a percentage of their weight at the age of 12 months are given in Table 5. This table shows that most of the body weight attained by 12 months of age is formed between the third and 10th months. After 10 months the gain in weight falls slightly.

TABLE 5. Growth of Tilapias per Month as Percentages of their Weight at the age of 12 Months (Results obtained in 1963)

Aquarium No.	No. of specimens	Months										
		0-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12
1L ₅	6	2,2	5,1	8,9	8,2	9,1	14,2	9,7	19,4	10,6	4,8	7,2
2L ₅	6	2,2	6,1	7,2	5,2	9,3	13,2	12,8	13,7	14,1	5,8	10,6
L ₁₀	6	1,7	5,5	6,7	9,3	12,3	14,4	14,2	11,2	9,5	3,7	11,0
L _{10a}	6	2,0	8,6	10,6	11,0	12,6	11,0	11,4	3,9	10,3	8,5	9,7
L _{5a}	12	1,9	6,3	15,0	11,2	10,9	12,0	10,7	7,5	9,6	8,0	6,4
Mean	18	2,0	6,3	9,7	8,9	10,8	12,9	11,7	11,1	10,8	6,1	9,0

Commas represent decimal points.

TABLE 6. Mean Length of Tilapias of Different Ages (in mm)

Aquarium No.	Age, months										
	2	3	4	5	6	7	8	9	10	11	12
1L ₅	41	62	80	96	110	121	130	142	151	156	160
2L ₅	41	64	81	91	99	116	128	138	146	153	159
L ₁₀	39	64	81	101	111	133	144	152	159	162	166
L _{5a}	40	66	89	103	113	125	131	139	143	147	152
L _{10a}	41	66	84	96	109	—	126	131	136	142	148
Mean	40,4	64,4	83,0	97,4	108,4	124,0	131,8	140,4	147,0	152,0	155,8

Commas represent decimal points.

The mean length and mean weight of tilapias month by month are given in Tables 6 and 7. The mean weight of tilapias receiving an animal diet increased from 1.2 g at the age of two months to 60 g at the age of 12 months. In experiments carried out in 1963 in which tilapias received plant food and their rate of growth was studied, fish were investigated between the ages of 8 and 14 months. The results of these experiments are described in our previous paper (N. V. Mironova, see this collection). As mentioned above, fish receiving an animal diet grew more intensively than fish receiving a vegetable diet.

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TABLE 7. Mean Weight (in g) of Tilapias of Different Ages

Aquarium No.	Age, months										
	2	3	4	5	6	7	8	9	10	11	12
1L ₅	1,4	4,6	10,2	15,5	22,6	30,0	36,1	48,2	54,8	57,9	62,4
2L ₅	1,4	5,1	9,6	12,8	16,6	26,6	34,5	42,9	49,3	55,1	61,6
L ₁₀	1,3	5,6	10,7	17,8	23,4	38,2	49,0	57,5	64,8	67,7	76,1
L _{5a}	1,0	5,3	12,6	18,7	24,6	31,1	36,9	41,0	45,7	50,5	54,0
L _{10a}	1,1	5,4	10,3	16,2	22,5	—	33,7	35,6	40,6	44,9	49,7
Mean	1,2	5,2	10,7	16,2	21,9	31,5	38,0	45,0	51,0	55,2	60,7

Commas represent decimal points.

Males and females grow equally until the age of 8-9 months. Thereafter, females begin to lag behind males appreciably in growth. Differences in weight and length increase with age. The mean weight of males aged 12 months in the aquaria was 67.7 g, compared with 47.7 g for females. The maximal weight reached by one male at the age of 27 months was 227 g.

REPRODUCTION

Tilapia mossambica Peters is a species in which the female incubates the eggs in her mouth. In the extensive literature on the biology of tilapia there are many reports of the necessity of a sandy soil for successful spawning of these fish, in which they dig a nest for laying the eggs. In our laboratory, spawning and subsequent incubation of the eggs took place successfully not only in aquaria with soil and vegetable matter, but also in 40-liter organic glass aquaria without soil or plants, and in groups of 4 or more fish.

The age of the females at the first spawning varies from 5 to 7 months (Table 8). Their weight ranges from 2.5 to 13.5 g and their length from 65 to 90 mm (mean 9.5 g and 83 mm). The frequency of reproduction varies from some females to others. On the average for the year for six females the interval between spawning was 40 days. It was much shorter for some females. For instance, for one female which spawned 11 times from March 16 to November 1, the mean interval over this period was only 20 days, varying from 17 to 26 days; by February this fish had spawned twice again and the mean interval had increased to 25 days. The minimal observed interval from one spawning to the next was 16 days. Reproduction took place during every month from February to January inclusive.

It is difficult to judge the fertility of the tilapias, because the eggs which have been laid are taken by the female into her mouth immediately after fertilization. However, it is possible to judge at least their minimal fertility from the number of fry reared from individual spawnings. A case was recorded when a female weighing 25 g laid 184 eggs; from a female weighing 30 g 209 young fish

were counted. In the ovaries of a female weighing 34 g, 339 eggs were found. In the ovaries of a female weighing 46.5 g 400 large eggs and 629 small eggs were found.

TABLE 8. Reproduction in Six Female Tilapias from February 18, 1963 to February 10, 1964

Indices	No. of females					
	5/12	10	8 ₁	5 ₂	8 ₂	4
No. of spawnings	13	8	9	9	6	3
Age at first spawning, months.	6	6	5	6	5	7
Weight, g	11	11	10	9	2,5	13,5
Length, mm	88	90	82	—	65	90
Mean interval between spawnings, days	25	41	44	38	71	60
t ^o min at time of spawning.	21,6	22,2	23,5	22,5	22,2	22,5
t ^o max at time of spawning	26,5	25,9	26,4	27,7	25,1	28,7
t ^o mean at time of spawning	23,9	24,2	24,8	24,8	23,5	26,1
t ^o mean during incubation.	24,1	24,9	25,0	24,1	24,0	26,1
Mean incubation time, days	11	11	11	9	9	—
Fertility.	90, 77 и >30	25, 60, 209, 20 & 41	31, 15, 184 & 70	102, 97 & 149	70 & 40	—
Number of larvae reared	90 & 77	60 & 209	—	—	—	—
Number surviving six months	42 & 77	14 & 204	—	—	—	—

Commas represent decimal points.

The duration of embryonic development until hatching of the larvae from the eggs was six days at a temperature of 23°. The duration of rearing of the eggs and larvae by the female (from spawning until liberation of actively swimming larvae with absorbed yolk sac) averaged 10 days.

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Spawning took place at temperatures between 21.6 and 28.7°, with a mean value of 24.4°.

For each incubation period the mean water temperature was calculated on the basis of two measurements during the day. The mean temperature for all incubation periods was 24.5°, but it varied in individual cases from 21.9 to 28.6°.

In 1963 young fish were reared in the laboratory from four layings of eggs. The number of fry in these layings was 90, 60, 77 and 209 fish. In the first case some of the fry died during the first month of life because of a breakdown in the air supply. In the second laying cases of disease were observed among the fry. The fry from the 3rd and 4th spawnings and fry reared in 1964 gave a survival rate of 100%.

The potential ability of the tilapia to increase its population rapidly can be judged from the pattern of its reproduction and the high rate of survival of its young.

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On the basis of the demands made on the animal components of the ecological system which were listed in the introduction the following preliminary assessment of the tilapia can be made.

1. With respect to the percentage of meat contained in its body the tilapia is close to other species of fish including the carp.
2. The tilapia is tolerant with respect to the conditions of its existence and, judging from the results obtained, it can live at a high stocking density, and under the stipulated temperature and oxygen conditions.
3. The tilapia can utilize a wide range of food products, both animal and plant. It readily eats the green parts of various vegetable plants, and thus satisfied one of the principal requirements.

Because of its frequent reproduction, the tilapia can quickly and regularly increase its population. Because of the comparatively high rate of growth, there are good grounds for expecting that this species can provide an adequate rate of increase of the total biomass of the population.

From the foregoing remarks it can be concluded that Tilapia mossambica Peters is a promising species for future research for the purpose of introducing it as a component in the closed ecological system.

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EFFECT OF FOOD SUPPLY ON GROWTH OF TILAPIA (TILAPIA
MOSSAMBICA PETERS)

N. V. Mironova and T. A. Skvortsova

The ability of the tropical African fish tilapia (Tilapia mossambica Peters) /498
to utilize the green mass of certain plant species was investigated in 1963 (N. V.
Mironova. See the present collection). The object of that investigation was to
discover whether the tilapia can be included in closed ecological systems as
transformers of parts of plants not usable by man into first-class food proteins.
The experiments were carried out on fish aged 8-13 months, i. e. , sexually
mature. In addition, fish grown in another laboratory and on various foods, in-
cluding animal food, were used. The results obtained thus gave an idea merely
of the extent to which the suggested plants could be eaten by the Tilapia and of
the amounts of them to be included in the diet of fish fed on plant food.

It was not ascertained whether the tilapia can feed on this range of plants
at an early age, whether it can live and grow on a purely plant diet, the effect of
feeding on a plant diet on the size of the young fish, and the nature of the plants /499
most readily eaten and producing best growth of the fish. Another interesting
problem is that of the effect of addition of a small amount of animal food to the
plant diet on growth of the fish.

To answer these questions an experiment was carried out in 1964 in which
tilapias were grown on various purely plant diets and mixed diets from an early
age.

One of the females spawned on April 6, 1964, and produced larvae on April
24. After three days the larvae were taken from the mother and transferred
into another aquarium. From that day and until the age of 48 days the larvae re-
ceived a small amount of vinegar eelworm. In addition, from the 14th day they
began to receive midge larvae ground in a mortar, and from the 19th day of life,
ground fresh sorrel. At the age of two months all the young fish were measured
and weighed (weight varied from 0.80 to 2.40 g), subdivided into nine groups
each containing 8 fish, and placed in identical aquaria made of organic glass and
with a volume of 40 liters. Starting from this moment the fish received food
strictly in accordance with the diet stipulated for each aquarium (Table 1). As
plant food they received sorrel, beetroot, radish and cabbage, i. e. , plants be-
longing to different families. The long vegetation period and the accessibility
of these plants meant that the fish could be maintained on the chosen diet until
the age of 7 months.

All the fish were fed until satiated completely. The diets differed therefore
not only in quality but also in quantity. Had the fish been given identical weights
of food, their rates of growth would have reflected only the comparative food
value of a particular item. The purpose of the experiment was different: to
establish the quantity of different foods which the fish could consume and the weight
they could attain when fed on different foods until complete satiation.

TABLE 1. Relative Percentages of Animal and Vegetable Foods in Diet of Tilapias of Different Groups in 1964

Aquarium No.	Number of Fish	Age, months				Species of Plants
		0-7		2-7		
		Animal food	Vegetable food	Animal food	Vegetable food	
5th aquarium (1963)	60	100	0	100	0	
26	8	69,8	30,2	75	25	Sorrel, beetroot, radish, cabbage (green leaves)
17	8	27,0	73,0	25	75	Sorrel, beetroot, radish, cabbage
23	8	26,4	73,6	25	75	Beetroot
21	8	26,1	73,8	25	75	Sorrel
25	8	27,1	72,8	25	75	Radish and cabbage
19	8	4,7	95,3	0	100	Sorrel, beetroot, radish, cabbage
22	8	2,3	97,7	0	100	Beetroot
20	8	2,1	97,9	0	100	Sorrel
24	8	2,5	97,5	0	100	Radish and cabbage

Commas represent decimal points.

Mean monthly 24-hour indices for fishes from different aquaria from 2 to 7 months of age are given in Table 2. For comparison this table, like all the subsequent tables, also include data for young fish grown in 1963 on purely animal food. The table shows the relationship previously observed (N. V. Mironova, see present collection) of a decrease in the 24-hour index with age and a higher absolute value of this index in fish receiving plant food only.

Tilapias not receiving animals food grew more slowly and by the age of seven months their length and weight were much smaller (Tables 3 and 4).

Fish receiving in their diet no more than 25% of midge larvae weighed no less than fish receiving 75 and 100% midge larvae (and in some cases exceeded them slightly). This suggests that to obtain a gain in weight equal to that of Tilapias fed on purely animal food, the diet need contain only 25%, or perhaps less, of animal food.

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In none of the cases listed above can the diet given to the fish be regarded as balanced. The diet was extremely monotonous and could not provide the fish with a complete range of essential food substances. Very probably the addition of small amounts of substances used for intensifying growth of livestock to the diet would probably have resulted in much higher indices of weight increase.

TABLE 2. Twenty-four Hour Index of Tilapias for each Month of Life (Mean Daily Amount of Food Consumed as Percent of Body Weight of Fish)

Food from age of 2 months, %		Aquarium No.	Age, months				
Animal	Vegetable		2-3	3-4	4-5	5-6	6-7
100	0	Young fish 1963	22	18	11	8	5
75	25	26	32	24	11	9	5
25	75	17	38	27	18	14	12
25	75	23	49	31	19	14	11
25	75	21	40	33	27	17	13
25	75	25	35	24	20	15	13
0	100	19	41	35	28	19	19
0	100	22	75	51	32	25	18
0	100	20	49	40	44	35	22
0	100	24	42	34	32	26	22

TABLE 3. Mean Length of Tilapias for each Month of Life (in mm)

Food from age of 2 months, %		Aquarium No.	Age, months					
Animal	Vegetable		2	3	4	5	6	7
100	0	Young fish 1963	40	64	83	97	109	122
75	25	26	47	67	84	103	119	128
25	75	17	45	62	79	93	105	116
25	75	23	44	66	82	95	110	122
25	75	21	47	67	85	101	115	131
25	75	25	45	63	77	88	102	112
0	100	19	45	61	72	83	88	95
0	100	22	44	57	69	79	83	87
0	100	20	45	60	71	83	94	103
0	100	24	46	61	72	84	92	101

TABLE 4. Mean Weight of Tilapias for each Month of Life (in g)

Food from age of 2 months, %		Aquarium No.	Age, months					
Animal	Vegetable		2	3	4	5	6	7
100	0	Young fish 1963	1,2	5,3	10,6	16,2	21,9	30,8
75	25 Sorrel, beetroot, radish, cabbage	26	1,7	4,9	10,5	17,5	28,4	35,7
25	75 Sorrel, beetroot, radish, cabbage	17	1,4	4,0	8,3	13,7	18,5	24,7
25	75 Beetroot	23	1,4	4,9	9,9	19,8	23,4	32,2
25	75 Sorrel	21	1,6	4,9	10,3	18,2	27,3	38,1
25	75 Radish and cabbage	25	1,4	3,9	7,5	12,0	17,8	22,5
0	100 Sorrel, beetroot, radish, cabbage	19	1,4	3,7	6,1	12,6	11,2	13,4
0	100 Beetroot	22	1,4	3,0	5,8	12,3	10,5	12,3
0	100 Sorrel	20	1,4	3,3	5,4	9,1	13,6	17,3
0	100 Radish and cabbage	24	1,5	3,6	6,1	9,5	13,2	16,4

Commas represent decimal points.

TABLE 5. Food Index of Tilapias for each Month of Life (Ratio Between Raw Weight of Food Eaten Per Month and Increase in Weight of Fish during this Period)

Food from age of 2 months, %		Aquarium No.	Age, months				
Animal	Vegetable		2-3	3-4	4-5	5-6	6-8
100	0	Young fish 1963	5,8	7,9	8,7	8,9	6,4
75	25 Sorrel, beetroot, radish, cabbage	26	9,9	9,9	6,9	5,7	7,1
25	75 Sorrel, beetroot, radish, cabbage	17	11,5	12,2	13,6	14,7	13,8
25	75 Beetroot	23	12,8	14,2	9,0	25,0	10,9
25	75 Sorrel	21	11,7	14,6	15,3	13,1	11,4
25	75 Radish and cabbage	25	11,6	12,6	13,7	11,7	11,9
0	100 Sorrel, beetroot, radish, cabbage	19	14,4	22,1	12,7		31,8
0	100 Beetroot	22	31,0	24,5	14,1		34,8
0	100 Sorrel	20	18,1	27,0	26,8	26,7	24,4
0	100 Radish and cabbage	24	15,1	22,1	23,0	23,8	21,9

Commas represent decimal points.

The food indices (Table 5) of the foodstuffs tested correspond to the results obtained for the increase in weight. When animal or mixed diets were given, a more rapid rate of growth and lower values of food indices were obtained. Conversely, fish fed on vegetable food grew more slowly and the values of their food indices were higher.

Table 6 summarizes the data for four groups of fish over a period of 7 months. The greatest mean weight was attained by tilapias receiving 75% midge larvae and 25% plant food. Second place was occupied by fish receiving animal food. They differed only very slightly from fish receiving no more than 25% of midge larvae, the rest of the diet consisting of green mass of various vegetables.

Tilapias receiving no animal food whatsoever were only half the weight of those receiving 25% midge larvae.

TABLE 6. Mean and Total Weight of Tilapia Fry at the age of Seven Months, Total Amount of Food Consumed During this Period and Food Index in Relation to Diet

Food, %		Number of aquaria	Number of fish	Mean weight of fish, g	Σ weight of fish, g	Quantity of food consumed, g			FI
Animal	Vegetable					Animal	Vegetable	Total	
100	0	5	60	30.8	1848	13 178	—	13 178	7.1
69.8	30.2	1	8	35.7	286	1 560	675	2 235	7.8
26.6	73.4	4	32	29.4	941	3 166	8 731	11 897	12.6
2.7	97.2	4	32	14.8	475	316	11 056	11 372	23.9

Clearly the age at which the tilapias are transferred to a purely vegetable diet is very important.

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The actual amount of the different foods given to the fish in order to reach a certain mean weight is shown in Table 7. These amounts are interesting as starting data for such investigations.

From these figures showing the gain in weight of the tilapias, their gain in weight per unit time per gram body weight can be calculated. Since the material at our disposal is still small, this calculation is approximate and provisional. The fish were weighed once a month. Information for the mean weight and gain in weight of the fish is therefore given relative to an interval of one month.

The results of this calculation are shown in Fig. 1. This was plotted from material for the growth of fish weighing from 1 to 58 g in nine experimental aquaria in 1968, and from summarized data for growth of tilapias in five aquaria in 1963 (Table 1).

TABLE 7. Total Quantity of Food Required for Growth of Tilapias of Different Ages and Weights

Aquarium No.	Proportion of food, %		Age, months									
			2		3		4		5		6	
			Mean Weight	Food eaten	Mean Weight	Food eaten	Mean Weight	Food eaten	Mean Weight	Food eaten	Mean Weight	Food eaten
	Animal	Vegetable										
1L _s	100	0	1,36	4,5	4,59	26,4	40,2	69,0	15,4	115,2	21,1	179,2
2L _s	100	0	1,4	4,5	5,15	33,1	9,6	70,9	12,8	105,4	16,6	145,9
L ₁₀	100	0	1,32	5,96	5,57	17,86	10,7	64,8	17,8	118,2	23,4	188,7
L _{5a}	100	0	1,05	4,3	5,34	29,3	12,6	87,9	18,7	141,5	24,6	179,8
L _{10a}	100	0	1,1	4,26	5,4	29,06	10,3	69,5	16,2	113,8	22,6	151,8
Mean			1,24	4,7	5,21	27,15	10,7	72,2	18,2	118,8	21,6	169,0
26	75	25 Sorrel, beetroot, radish, cabbage	1,7	10,9	4,9	43,1	40,5	98,6	17,5	147,7	28,4	210,7
17	25	75 Sorrel, beetroot, radish, cabbage	1,4	10,9	4,0	41,3	8,3	94,8	13,7	167,2	18,5	238,5
23	25	75 Beetroot	1,4	10,9	4,9	56,4	9,9	127,4	19,3	216,9	23,4	306,9
21	25	75 Sorrel	1,6	10,9	4,9	49,4	10,3	127,9	18,2	249,4	27,3	368,4
25	25	75 Radish and cabbage	1,4	10,9	3,9	39,9	7,5	81,9	12,0	147,4	17,8	216,4
Mean			1,4	10,9	4,4	46,7	9,0	108,7	15,8	195,2	21,7	282,5
19	0	100 Sorrel, beetroot, radish, cabbage	1,4	10,9	3,7	42,8	6,1	97,3	12,6	179,8	11,2	247,8
22	0	100 Beetroot	1,4	10,9	3,0	61,4	5,8	131,9	12,3	222,9	10,5	307,9
20	0	100 Sorrel	1,4	10,9	3,3	45,4	5,4	103,9	9,1	200,4	13,6	319,9
24	0	100 Radish and cabbage	1,5	10,9	3,6	43,4	6,1	97,9	9,5	175,4	13,2	265,4
Mean			1,4	10,9	3,4	48,2	5,8	107,0	10,9	194,6	12,1	285,2

Commas represent decimal points.

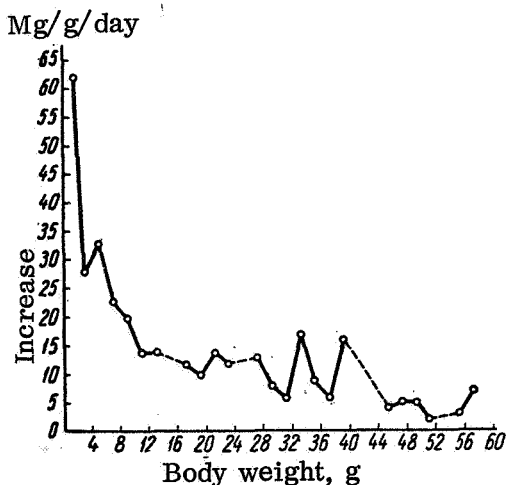


Figure 1. Increase in Weight of Tilapias.

For a body weight of up to 2 g the daily increase in weight is 62 mg/g body weight. For a body weight over 50 g the daily increase falls to 2-7 mg.

The results of this investigation show that tilapias can utilize the green mass of higher plants not merely in the adult, sexually mature state, but also from the age of two (or even one) months, when their body weight is about 1 g. Thereafter they can live and grow for long periods (5 months) when fed purely on vegetable food, even if this consists only of plants of one species. A small addition by weight of animal food has a considerable influence under these circumstances on the rate of growth, doubling it compared with the growth of fish receiving vegetable food only.

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The results described above demonstrate the considerable plasticity of growth of the tilapia and the possibility of its intensification by the addition of small amounts of first-class food (for example, waste products from the fish themselves resulting from cooking, Chlorella, and perhaps vitamins).

Further investigations will be carried out to study methods of increasing growth of the tilapia.

COMPARISON OF GROWTH OF TILAPIAS (TILAPIA MOSSAMBICA
PETERS) WHEN FED ON CHLORELLA AND OTHER
FOODSTUFFS

N. V. Mironova

During the investigation of the possibility of including the tilapia in a closed ecological system the question of its ability to consume Chlorella, in addition to the tops of vegetable plants, utilization of which has previously been established [1, 2], must be considered. Besides demonstrating the possibility of feeding tilapias on Chlorella and maintaining them on this food, it is most important to establish the gain in weight of the fish attainable on this diet and the value of the food index. It has been reported in the Western literature that Tilapia mossambica can survive for a long time on Chlorella alone, but under these conditions the fish grows slowly and does not reproduce [3].

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The first attempts at feeding tilapias on Chlorella were made by the author in August 1965. Chlorella for the experiments was kindly provided by the laboratory of mass cultivation of algae, BINII, Leningrad State University, for which the author is most grateful.

Experiments were carried out initially to determine whether tilapias would eat Chlorella. Dried Chlorella was given as a 10% additive to tilapias fed on sorrel. To prevent its dispersion in water the freeze-dried Chlorella (strain No. 4 BINII, June, 1965) was mixed with agar agar (4 g agar agar/100 g Chlorella), dried by heat, and shredded. The fish immediately began to eat it eagerly, but having taken it into their mouths they often rejected it and it was not always easy to ensure that all the Chlorella preparation was eaten. Later, the fish were given compressed pieces of freeze-dried Chlorella. The fish ate this so readily that only a very small quantity was wasted in the water.

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The mean weight of three tilapias aged 8 weeks when they began to receive Chlorella as a food additive was 10.6 g. By six months their mean weight was 34.7 g. The gain in weight during feeding for three months on sorrel (90%, fresh weight) with addition of Chlorella (10% dry weight) averaged 24.04 g. Meanwhile young fish from the same batch of eggs fed on sorrel alone gained 20.58 g in weight and attained a weight of 27.9 g. The 24-hour and food indices for these latter fish were much higher (Table 1).

Hence, addition of Chlorella to a vegetable diet increased the rate of growth of the tilapias and considerably reduced the 24-hour and food indices.

Later, two series of experiments were carried out in which tilapias were fed on Chlorella from the earliest age. In both series fish from the same batch of eggs were used in the experiment. All experiments were carried out in identical organic glass aquaria 40 liters in volume. The water temperature during the first six months of life of the fish varied between 19.4 and 31.3°. These limiting

TABLE 1. 24-Hour and Food Indices for Tilapias fed on Sorrel with Addition of Dried Chlorella and on Sorrel Alone*

Age, months	24-hour index		Food Index	
	Sorel + Chlorella	Sorel	Sorel + Chlorella	Sorel
3—4	34,2	60,8	22,0	31,4
4—5	28,1	41,7	19,8	28,4
5—6	19,5	24,9	23,4	27,2

*For calculating the 24-hour and food indices the weight of sorrel and Chlorella were equalized as dry substances. Dry weight is taken as the basis for calculation.

Commas represent decimal points.

values of temperature were single isolated deviations from the usual mean temperature. The mean monthly temperature in six aquaria during six months varied from 23.8 to 25.8°.

Series I consisted of two groups, each containing 10 fish (aquaria Nos. 40 and 40a). On reaching the age of sexual maturity, the fish in aquarium 40 were found to consist of five females and five males, and in aquarium 40a, three females and seven males.

During the first month of life these fish received living vinegar eelworms, minced midge larvae as fresh food and freeze-dried Chlorella, fish meal, and dried yeast as dried food. The total amount of food given during this month was not measured. At the age of one month the young fish were weighed in catches of 20 and placed in two aquaria, with 20 fish in each. The mean weight of the fish in aquarium No. 40 was 0.183 g and in aquarium No. 40a 0.203 g. From the age of about two months, 10 fish were left in each aquarium. From the age of one month and until nine months the fish in aquarium 40 received only freeze-dried Chlorella (Chlorella pyrenoidosa, strains No. 4 and No. 157 BINII, 1965).

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The diet of the fish in aquarium 40a consisted of 75% Chlorella and 25% fish meal. The total quantity of food was the same in both aquaria. Only after the age of 8 months did the tilapias in aquarium 40a begin to eat their food less satisfactorily and the total quantity of food eaten by them per month was rather less than that eaten by the fish in aquarium 40. The daily ration of dry Chlorella per fish ranged from 0.3 g at the age of two months to 0.6 g at the age of 7-9 months.

Series II consisted of four groups each containing 10 fish (aquaria 41a, 41b, 41d, 41e). In contrast to series I the larvae were placed in groups of 10 in separate aquaria on the 6th day after the female ejected them for the first time

TABLE 2. Mean Length of Tilapias of Different Ages
(in mm)

Aquarium No.	Food, %			Age, months								
	Chlorella	Fish meal	Midge larvae and tubifex									
				1	2	3	4	5	6	7	8	9
40	100	—	—	—	40,9	71,3	89,4	109,9	124,2	136,2	147,0	157,1
40a	75	25	—	—	52,4	77,2	92,2	109,3	124,2	137,0	147,2	153,5
41a	100	—	—	—	47,6	69,2	85,6	107,5	118,9			
41b	75	25	—	—	47,6	66,8	85,7	98,2	107,8			
41d	50	—	50	—	60,2	86,5	103,8	117,8	127,2			
41e	—	—	100	—	58,1	82,6	98,3	116,7	127,8			

Commas represent decimal points.

from her mouth. From the same day the fish in each aquarium began to receive the stipulated diet with strict quantitative measurement of the food given. In aquarium 41a the fish received (just as in aquarium 40) dried Chlorella only. In aquarium 41b the diet consisted of 75% Chlorella and 25% fish meal. In aquarium 41d the fish received 50% Chlorella and 50% of animal food consisting of midge larvae, tubifex, Chaoborus, and a few water fleas. The quantity of living animal food was five times greater than the weight of dried Chlorella given (the conversion factor of five was determined by drying these foodstuffs to constant weight in a muffle furnace). Finally, in the fourth aquarium (No. 41e), the fish received animal food only in a quantity 5 times greater than the weight of dried Chlorella given to aquarium 41a. The quantity of food given to the fish was thus the same when expressed as dry weight, just as in the first series.

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The mean length, mean weight, gain in weight, and the 24-hour and food indices of these fish for each month of life in relation to the diet received are given in Tables 2-6. Since the fish of series II attained the age of only six months, it is possible to compare all these indices only for fish until this age.

Comparison of the mean weight and the food indices is of the greatest interest. Table 3 gives data for mean weight; this table shows that the mean weight of tilapias fed on Chlorella alone differed only slightly from the mean weight of tilapias receiving fish meal in addition to Chlorella. In both series at the age of four months the latter were slightly heavier, but by six months the weight of the fish in both aquaria of series I was the same, and in series II the fish fed on Chlorella were slightly heavier than those fed on a mixture of Chlorella and fish meal.

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The differences in weight of the fish at the age of six months were somewhat greater in the two series. The fish of series I at six months were larger than those of series II. This difference appeared only after the age of 5 months. In aquaria 40 and 40a until the age of 9 months no spawning took place, whereas in aquarium 41a, after the fish had attained the age of 5 months, three females spawned four times over a period of 28 days and in aquarium 41b one case of spawning took place in the same period.

TABLE 3. Mean Weight of Tilapias of Different Ages (in g)

Aquarium No.	Food, %			Age, month								
	Chlorella	Fish meal	Midge larvae and tubifex									
				1	2	3	4	5	6	7	8	9
40	100	—	—	0,183	2,04	6,40	12,55	22,6	32,3	40,7	51,8	62,9
40a	75	25	—	0,203	2,48	7,68	13,18	21,6	32,3	41,6	49,5	55,1
41a	100	—	—	0,315	2,28	8,94	12,20	22,4	28,7			
41b	75	25	—	0,478	2,92	8,06	15,10	20,5	26,5			
41d	50	—	50	0,557	3,72	11,94	19,60	28,1	33,8			
41e	—	—	100	0,423	3,22	11,02	18,5	29,1	35,2			

Commas represent decimal points.

TABLE 4. Increase in Weight of Tilapias for each Month of Life (in g)

Aquarium No.	Food %			Age, months								
	Chlorella	Fish meal	Midge larvae and tubifex									
				1	1-2	2-3	3-4	4-5	5-6	6-7	7-9	8-9
40	100	—	—	0,183	1,85	4,39	6,15	10,05	9,7	8,4	11,1	11,1
40a	75	25	—	0,203	2,27	5,20	5,50	8,46	10,7	9,3	7,9	5,5
41a	100	—	—	0,315	1,97	6,66	3,26	10,20	6,3			
41b	75	25	—	0,478	2,44	5,14	7,04	5,39	6,0			
41d	50	—	50	0,557	3,17	8,22	7,67	8,50	5,7			
41e	—	—	100	0,423	2,79	7,80	7,50	10,64	6,0			

Commas represent decimal points.

Fish from the same batch of eggs receiving living animal food at the same age were somewhat larger than fish not receiving this food; the difference, however, was not great, 33.8-35.2 g compared with 26.5-32.3 g. It is interesting to note that fish below the age of four months receiving Chlorella in addition to animal food were heavier than tilapias receiving only midge larvae and tubifex.

The food index calculated per dried foodstuff (i. e. , equal to one-fifth of the weight of the living animal food) varied on individual months from 1.0 to 2.7. High values of food indices below the age of one month must evidently be attributed to incomplete consumption of the food, wastage of which could not be estimated.

TABLE 5. Food Index of Tilapias of Different Ages

Aquarium No.	Food, %			Age, months								
	Chlorella	Fish meal	Midge larvae and tubifex	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9
40	100	—	—	—	1,30	1,90	1,91	1,33	1,23	1,37	1,49	1,67
40a	75	35	—	—	1,04	1,64	2,14	1,58	1,12	1,22	2,08	2,47
41a	100	—	—	5,70	2,67	1,36	2,70	1,25	1,70			
41b	75	25	—	3,80	2,16	1,77	1,27	2,00	2,07			
41d	50	—	50	—	5,0(1,6)	3,35(1,12)	3,52(1,17)	3,8(1,29)	6,29(2,10)			
41e	—	—	100	—	9,5(1,9)	5,7(1,14)	5,60(1,0)	5,1(1,02)	9,65(1,93)			

TABLE 6. 24-Hour Index of Tilapias of Different Ages

Aquarium No.	Food, %			Age, months								
	Chlorella	Fish meal	Midge larvae and tubifex	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9
40	100	—	—	—	7,50	6,56	4,15	2,38	1,46	1,09	1,19	1,04
40a	75	25	—	—	6,04	5,51	3,76	2,40	1,48	1,07	1,22	0,85
41a	100	—	—	—	14,00	5,22	2,86	2,11	1,51			
41b	75	25	—	—	10,76	5,33	2,67	1,95	1,68			
41d	50	—	50	—	8,54	3,78	1,90	1,52	1,22			
41e	—	—	100	—	10,00	4,03	1,68	1,52	1,13			

Commas represent decimal points.

TABLE 7. Mean Weight of Tilapias, Quantity of Food per Fish, and Food Index

Aquarium No.	Food over six months											
	Chlorella	Sorrel	Fish meal	Midge larvae	Tubifex	Chaoborus	Water fleas	Total	Total as dry substances	Mean weight of fish, g	Food index as fresh substance	Food index as dry substance
40	47,97	—	—	—	—	—	—	47,97	47,97	32,3	7,4	1,48
41a	48,80	—	—	—	—	—	—	48,80	48,80	28,7	8,8	1,70
40a	35,99	—	11,97	—	—	—	—	47,97	47,97	32,3	7,4	1,48
41b	35,45	—	12,14	—	—	—	—	47,59	47,59	26,5	8,9	1,70
35	30,20	347,77	5,4	8,88	8,41	—	0,31	400,97	82,00	34,7	15,0	2,36
20	—	311,3	—	7,40	—	—	—	318,70	39,89	13,6	23,4	2,93
37	—	706,73	—	7,90	4,27	—	0,31	719,21	89,69	27,9	25,7	3,21
41d	24,26	—	—	50,20	55,70	11,5	3,7	145,36	48,50	33,8	7,1	1,43
Aquarium	—	0,72	—	159,36	9,26	—	0,97	170,32	34,06	21,9	7,7	1,55
1963	—	2,45	—	298,96	13,77	—	0,31	313,18	62,60	44,7	7,2	1,40
32	—	—	—	97,85	100,57	24,5	8,48	231,40	46,30	35,2	6,5	1,31
41e												

Commas represent decimal points.

Table 3 shows that the mean weight of tilapias fed on Chlorella alone (aquarium 40) differed very slightly from that of fish fed on living animal food.

It is interesting to compare the weight attained by tilapias at the age of six months when fed on Chlorella and when fed on purely vegetable food. This comparison is made in Table 7.

When examining the data in Table 7 two features must be borne in mind. To compare the results of the 1966 experiments on tilapias fed on Chlorella with the results of experiments on fish fed on other foods, material obtained during investigations in earlier years is also used: aquarium 20 in 1963 and 1964, aquaria 32, 35, 37 in 1965. Comparison of the mean weight and food indices for fish kept on the same diet shows that in the later experiments higher growth indices were obtained (in aquarium 37 than in aquarium 20 and in aquarium 32 than in the aquaria in 1963).

In the 1966 experiments fish kept on different diets received the same quantity of food by weight. Because of the decrease in the food consumption by fish in aquarium 1 it was impossible to increase the ration in the other aquaria of that series. In aquarium 41e, for instance, the fish ate hardly any of the midge larvae and tubifex given to them; thus preventing an increase in the ration of Chlorella in aquaria 41a and 41b. However, the eagerness with which the fish

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in these aquaria (just as in aquarium 40) ate the Chlorella shows that the quantity of Chlorella given to the fish could have been increased and, consequently, a greater mean weight of the tilapias fed on Chlorella could have been obtained.

After these remarks we can examine the data in Table 7. The mean weight of the tilapias at six months in aquarium 20 and in the 1963 aquaria must be regarded as much below the possible weight. Comparison of the weight of fish fed on sorrel, Chlorella or animal food in all the other aquaria, however, shows that their weight differed only slightly: fish fed on sorrel 27.9 g, on Chlorella with fish meal 26.5 and 32.3 g, fed on pure Chlorella 28.7 and 32.3 g, fed on animal food 35.2 and 44.7 g; the mean weight of the fish fed on Chlorella may be increased by increasing the amount of Chlorella given.

Comparison of the food indices shows that if the food eaten by the fish is expressed as dry substance the food indices for the fish receiving Chlorella and for those receiving animal food are of the same order: 1.48-1.70 compared with 1.31-1.40. The food indices for fish receiving sorrel, however, are much higher (23.4-25.7 per fresh weight of sorrel and 2.93-3.21 when expressed per dry substance).

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To sum up, tilapias can eat dried Chlorella (freeze-dried) extremely readily and extract it almost completely from the water. At the age of 4-6 months the mean consumption was 0.4 g dried Chlorella per fish. On such a diet the fish attained a weight close to the weight of fish receiving animal food. Fish receiving sorrel with the addition of 10% dried Chlorella attained the same weight. Similar remarks apply to the food indices. Chlorella can thus be regarded as a first-class food for growth of tilapias intended for human feeding in closed ecological systems.

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EFFECT OF VIBRATION AND LINEAR ACCELERATIONS ON FISH

V. Ya. Mamontov and G. B. Mel'nikov

There are definite prospects for including fish in the closed cycle of matter. However, this presents problems to the research worker because the inclusion of a new link in the ecological system of the spacecraft requires a comprehensive study of this link, of its relationship to the other links in the process of metabolism, and the influence of extreme factors of space flight on it. /512

The inclusion of new groups of animals and plants in the closed cycle of matter on board the spacecraft calls for the study of the pattern of their reaction to the combination of extreme factors encountered during space flight.

The object of this investigation was to study the effect of vibration and linear overloads on fish in order to examine the influence of these extreme factors on them.

EXPERIMENTAL METHOD

Experiments were carried out on goldfish (*Carassius auratus gibelio* Bloch). The weight of the experimental fish varied from 49.65 to 131.3 g and their length from 16.0 to 21.0 cm. Before the experiment the fish were kept under aquarium conditions for the five months of autumn and winter. Before the experiments began the fish were carefully selected and tagged. The external appearance, movements and responses to stimuli of the selected fish were normal. Their body surface showed no signs of injury or disease. /513

Tests of vibration acceleration were carried out on the VEB-Geräte und Regeler Werke 20-1000 vibration bench. The fish were kept in an organic glass aquarium with a capacity of 9 liters. In experiments with vibrations in the frequency band 20-300 Hz the aquarium was tightly closed with a lid to prevent the water from spilling. In the experiments with frequencies above 300 Hz the aquarium was opened. In all the experiments water filled two-thirds of the total capacity of the aquarium, so that during vibrations waves were formed in the upper layers of the water (depending on the frequency and amplitude of the oscillations), and these exerted a definite additional influence on the fish if they came into the zone of these waves. Tests were carried out at the following frequencies: 20, 30, 50, 70, 80, 100, 300, 500, and 1000 Hz. In all the experiments vibration accelerations of about 10 units were created. At a given frequency of vibration such an acceleration was achieved by increasing the amplitude of the waves for 1-2 sec after the beginning of vibration.

The method mainly used to record behavior of the fish during exposure to vibrations was by taking motion pictures at a frame speed of 24/sec. The following cameras were used to take the pictures: "Rodina" ZKSKh, objective

75 mm; AKS-4, objective 50 mm. The object was illuminated by two KPL-35 projectors with a PZh-18 (5 kW) lamp. The filming program was as follows: a) to record the state of the fish before exposure to vibration pictures were taken for 15 sec; b) pictures were taken when the vibration bench was switched on and thereafter every 15 sec throughout the experiment. The working time of the camera in each filming period was 20 sec. Hence, during an experiment lasting 6 min, pictures were taken for 4 min; c) 10 min after switching off the vibration bench pictures were taken for 15 sec to record the aftereffects of vibration and also the initial stages of the period of recovery of normal behavior of the experimental fish.

Experiments in which the fish were exposed to linear overloads were performed on a centrifuge with maximal radius 500 mm.

The fish were kept in a hermetically sealed aquarium with capacity 4 liters, placed on a special mounting panel. The behavior of the fish during exposure to linear overloads was recorded on motion pictures taken with an AKS-2 camera, objective 35 mm. The object to be photographed was lit by two illuminators each fitted with 12 SM-15 lamps (2 V, 10 W). The camera, the aquarium with the fish, the mounting panel and the illuminators were all placed on the platform of the centrifuge. For close-up photography the transition ring for the objective was calculated and special conditions of photography worked out. In all experiments the fish was exposed to an overload not exceeding 20 units for various times, not exceeding 10 min. Tests were carried out in two variants: 1) overloading during acceleration of the centrifuge to the assigned speed followed by breaking to a complete halt; 2) prolonged exposure to overloading of between 2 and 10 min.

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The conditions of photography were chosen in accordance with these variants. The aquarium in which the experimental fish were placed was filled with water in two different ways: 1) to two-thirds of its capacity; 2) completely.

RESULTS AND DISCUSSION

When starting our study of the effect of vibrations on aquatic organisms we could find no references in the literature to the influence of this extreme factor on fish. Although the present investigations may be regarded as preliminarily, the very first experiments drew attention to certain aspects distinguishing the behavior of fish when exposed to vibrations of various frequencies. These were due primarily to the properties of the medium in which the fish lived relative to different vibrations. Water is, of course, a physical medium in which waves spread faster and further than in air. In this respect water resembles a solid body in its physical properties. Consequently, the effects of vibrations may be expected to be stronger on aquatic organisms than on terrestrial animals.

Whereas terrestrial animals experience the action of vibration from a vibrating surface with which they are in contact and the vibration overloading acts in the direction in which the surface vibrates, fish in a limited volume of water experience the effect of vibration in many directions. The floor, walls and lid (if present) of the aquarium all vibrate, and these vibrations are transmitted

by the column of water to the body of the fish in many directions. In addition, when water in an aquarium vibrates, static waves are formed on its surface, and if the fish comes into their zone it experiences additional effects from oscillation. Probably in the case of vibration of organisms in water it is impossible to speak of a strict direction of the vibration overload, more especially because the body of the fish is constantly changing its position relative to the vibrating walls of the tank. However, the principal direction from the source of vibrations and from that wall of the tank in contact with it is chosen. In our experiments vibration overloading acted on the body of the fish from below upward in a ventro-dorsal direction.

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Another feature to which our attention was directed before the experiments began was that fish possess a special organ receiving oscillations of different frequencies, and receiving oscillations of low frequencies from 5 to 30 Hz particularly well [2]. This is the lateral line organ with its numerous ramifications of nerves along the whole surface of the body of the fish. Consequently, rapid excitation of the nervous system of the fish and sharp changes in behavior may be expected in view of the direct effect of even weak vibrations on the lateral line receptor, and not merely through tactile receptors as in terrestrial animals. The third feature to which attention was drawn before the experiments is the completely unusual nature of the vibration as the stimulus for fish, although they are also unusual for other animals. For fish, which under natural conditions live in the quiet of deep waters and completely avoid sudden oscillations of water in any of its manifestations, vibrations of different frequencies and with considerable vibration overloads can be regarded as a powerful extreme factor. On these grounds we assumed that exposure of fish to the vibrations would have considerable consequences, and this was confirmed by the experiments.

Our assessment of the degree of action of vibrations on the fish was based on observations on the state of the following physiological function: a) movement of the gill covers (respiratory rhythm); b) general motor activity; and c) the balance reaction (changes in the position of the body of the fish relative to normal).

The experiments showed that vibrations of different frequencies, but with equal overloads (about 10 units) and acting for the same time (6 min) gave different effects on the fish. For instance, vibrations with frequencies within the range 20-40 Hz had an effect characterized by an increase in the frequency of respiratory movements, sometimes of considerable strength; an increase in motor activity from slight general movement to sudden and powerful swimming movements. During vibrations with frequencies of 20-40 Hz the fish began to dart to different sides of the aquarium as if avoiding the zone of vibration. No changes in the balanced reaction were observed.

Vibrations with frequencies of 50-70 Hz had quite the opposite effect on the fish from vibrations with frequencies of 20-40 Hz. The respiratory movements became slower, and arrhythmia was observed, varying from a slight degree to paroxysmal movements of the gill cover. In experiments with a frequency of 70 Hz, by the end of the third minute of action of vibration the respiratory movements became superficial, and often of "Cheyne-Stokes" type. The motor

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activity was affected just as in response to low frequencies. At the beginning of action of vibrations with frequencies of 50-70 Hz, a sharp decrease in motor activity was observed. The fish was in a "stunned" condition, falling to the bottom of the tank and remaining motionless for 2-3 min. The body of the fish listed slightly to the side, although the list was easily corrected during the first minutes of exposure to vibration. A further intensification of the vibration gave rise to a persistent disturbance of equilibrium. The fish turned over on its side and tried to restore the normal position of its body by sharp swimming movements (Figs. 1, a, b, c). Sometimes circular movements in a vertical plane with the fish on its side were observed. After discontinuing vibration the recovery period lasted about 1 h before the fish was normal again.

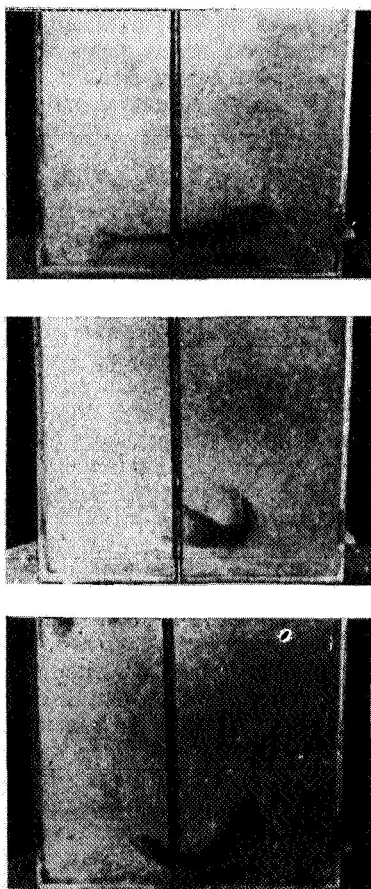


Figure 1. Action of Vibration (50-70 Hz) on Fish (a, b, c).

Frequencies of 80-90 Hz in our experiments have the strongest effect on the fish, sometimes lethal. Death was observed more than once 5-6 min after the beginning of vibration. Movements of the gill covers became very rapid and paroxysmal during the first minute of the experiment, and gradually changed into superficial and hardly visible movements. From being sharply increased initially, motor activity diminished until the fish were completely motionless. Only slight movements of the fins and tail were observed. Severe disturbances took place in the body equilibrium of the fish. From a strong list at the beginning of the experiment, they developed until the fish turned over onto its side, and after about 4 min of the experiment, it completely lost its balance. The body of the fish assumed any position in space, most frequently vertical, with its head down, and less frequently horizontal, on the floor of the aquarium with its ventral aspect upward (Fig. 2).

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With an increase in the frequency of vibration from 100 to 1000 Hz, the effect of vibration on the fish became less pronounced. The pattern observed in experiments with low frequencies (20-50 Hz) was repeated.

After the action of vibration was discontinued in the experiments, the pattern of recovery of the normal state of the fish differed. The investigated frequencies also differed sharply from one another. After vibrations with frequencies of 20-30 Hz, complete recovery of respiration and of normal swimming movements was observed within 10-15 min after the experiment. After the action of vibrations with frequencies of 50-70 Hz, the recovery period extended for



Figure 2. Action of Vibration (80-90 Hz) on Fish.

between 30 min and 1 h. After vibrations with frequencies of 80-90 Hz, recovery of the normal state was prolonged, lasting several hours, unless the fish died during the experiment. Sometimes, even after complete recovery had taken place and all external signs were normal, the fish died 1-2 days after the experiment.

In the character of the recovery period, the experiments with vibrations of frequencies between 100 and 1000 Hz were similar to those with frequencies of 20-50 Hz. For a rapid assessment of the degree of the general effects of vibration of the fish, we used a scale based on a six-point system.

Exposure to vibration of 0-3 points on our scale was tolerated perfectly satisfactorily by the fish. This vibration had no significant effect on the subsequent existence of the fish.

Vibrations of 4-5 points caused serious disturbance of the normal activity of the fish (disturbance of movement coordination, loss of balance, disturbance of respiratory movements of the gill covers, etc.). The fish tolerated exposure of this type badly, and although recovery of the normal condition of the fish according to external signs was observed, this does not rule out the possibility that the internal organs of the fish could have received injuries, the aftereffects of which will appear much later.

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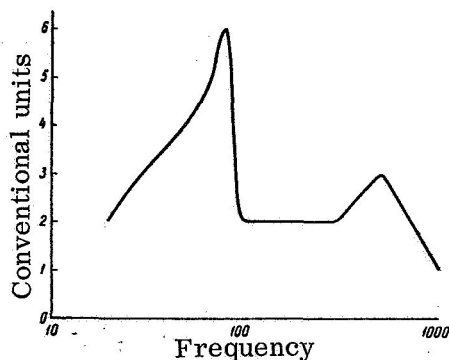


Figure 3. Frequency Characteristics of Action of Vibration on Fish.

Vibrations of six points proved lethal to the fish, and this assessment is made essentially after death of the fish either during the experiment or within 1-2 h thereafter.

Analysis of motion pictures of the experiment and of their written record shows that the degree of the effect of vibration on the fish varied with the frequency of vibration for equal overloads and equal times of action (Fig. 3).

Because of the sharp increase in the severity of the effects of vibration with frequencies of between 80 and 90 Hz, it seems possible that the resonance phenomena occur in this frequency band for fish 16-21 cm in length and 50-100 g in weight. This frequency band of vibrations is the most dangerous for fish of this species.

Scale for Assessing General Effects of Vibration on Fish

Severity of effect on fish	Points	State of physiological functions			Recovery period to normal after vibration
		Respiratory rhythm	Motor activity	Reaction of balance	
Absence of visible effect	0	Normal	Normal	Normal	
Very slight	1	Slightly increased	Slightly increased	Normal	5 min
Weak	2	Increased, sometimes greatly increased	Sharply increased	Normal	10 min
Moderate	3	Slowed	Decreased, "stunned"	Normal or slight listing	10-30 min
Strong	4	Arrhythmia, paroxysmal respiration	Sudden movements. Circular movements lying on side	Turning over on side, finds balance with considerable difficulty	1 hour
Very strong	5	Superficial respiration	Weak movements only of fins and tail	Complete loss of balance, body of fish assumes any position in space	Recovery within a few hours
Lethal	6	Respiratory movements absent	Movements absent	Complete loss of balance. After experiment fish lies on side on surface of water or on floor of tank	Death during first six minutes of experiment, sometimes a few days after experiment

As mentioned previously in the section "Experimental Method," we carried out experiments to study the effect of linear overloads caused by rotation on a centrifuge on the fish. It must be mentioned at once that these investigations were not intended for the purpose of determining limits of tolerance of the fish to linear acceleration. It is well known that organisms living in water tolerate linear overloads much better than organisms in an air environment. This is due primarily to the physical properties of the aquatic environment itself. Water considerably attenuates the action of acceleration on the body and the overload arising as a result. Because of the water surrounding the fish, the overload is uniformly distributed over the whole body, and the fish therefore does not experience local effects of overloading on different parts of its body. The limits of tolerance to overloads are thereby considerably increased. When studying this problem of tolerance to overloads by aquatic animals, Morris and Beischer [3] showed, for example, that small fish can withstand colossal accelerations of up to 10,000 g for 30 sec. Fish can withstand such unusually high overloads entirely because of the water surrounding their body. Resistance to considerable overloads has also been observed in aquatic invertebrates.

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We also set out to determine the character of the behavior of fish when exposed to linear overloads. In experiments on the centrifuge the fish were exposed to accelerations not exceeding 20 units, but were kept in aquaria filled with water up to different levels. In aquaria completely filled with water, after the first few seconds of rotation of the centrifuge and of increase of centrifugal force, the fish adopted a position so that the radial acceleration acted sideways, transversely to the body axis. It was noted that the fish arched its body in such cases to the side opposite to the action of the centrifugal force (Fig. 4).

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Figure 4. Action of Acceleration on Fish in a Completely Filled Aquarium.

Sometimes in these experiments the fish adopted a similar position of its body, but with its ventral aspect uppermost. This is probably because in the initial moments of increase of acceleration the fish makes sudden swimming movements, loses its balance, and adopts an incorrect position in space [4], fixing its body apparently in such a position that it can resist the increasing overload. During the action of overloads of 10-15 units or more, no movements of the gill covers whatsoever can be observed. It may be postulated that prolonged exposure to overloading essentially disturbs the breathing of the fish, although it may have suffered no other injury. In our experiments the normal rhythm

of respiration was restored 40-60 min after the procedure, but the normal body position and normal swimming movements were restored after 1-2 min.

The behavior of the fish was very unusual in experiments in which the aquarium was only half or two-thirds filled with water. In these experiments, as the centrifugal force increased the water was deflected toward the side wall



Figure 5. Action of Acceleration on Fish in an Aquarium Partly Filled with Water (a, b).

of the aquarium (the position of the meniscus was vertical). The fish was apparently thrown out of the water and found itself in the air, where it made sharp movements and tried to get back into the water (Figs. 5, a, b).

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This may be explained as follows: in our experiments we used a goldfish, the specific gravity of which according to data given by Yu.G. Aleyev [1], is 1.0-1.01; nevertheless, the presence of air in the swim bladder makes the central part of the fish's body lighter than water, and it is left behind when the water moves. This causes the body of the fish to curve into an arch in the experiments in which the aquarium is completely filled with water (Fig. 4). It may naturally be assumed that fish without a swim bladder, or with a very small bladder (whose specific gravity is much greater than that of water), cannot assume such a position.

The experiments to study the effects of linear overloads thus showed that the size of the air cushion in the aquarium is important for the fish.

If acceleration acts for a long time on a fish whose body has a specific gravity equal to that of water and large swim bladder, placed in an aquarium with a large air cushion, death of the fish may be hastened by its being thrown out of the water and being exposed to the action of acceleration in an environment of air, preventing the alleviating influence of the water surrounding the body of the fish.

Linear overloads of 20 units acting for a period of from 2 to 10 min are tolerated by fish with comparative ease. However, allowance must be made for the extent to which the vessel in which the fish is kept is filled with water, and for the specific gravities of the experimental fish.

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ACTION OF γ -RAYS AND PROTONS ON CHLORELLA

I. D. Anikeyeva, E. N. Vaulina and V. A. Shevchenko

Investigations conducted on a strict radiobiological plane for the quantitative estimation of the radioresistance of Chlorella have been published recently [1-6].

They include studies of the action of ultraviolet rays on the survival rate and mutation of Chlorella. The radiosensitivity of Chlorella (LD_{50}) was found to vary for different strains and under slightly different experimental conditions from 9 to 15 kR.

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The object of this investigation was to study the action of protons and γ -rays on the survival and mutation rates of Chlorella.

Experiments were performed on Chlorella vulgaris strain LARG-1. A suspension was synchronized in the usual manner [1] and 2 ml of it sealed into glass ampules 5 cm³ in volume. The density of the suspension was 1.10^6 cells/ml. The ampules were then wrapped in dark paper, in which they were irradiated and kept until required for seeding.

The cells were irradiated with Co^{60} γ -rays and protons with an energy of 660 MeV. The doses of protons and γ -rays used were equal and the periods of irradiation were similar. The doses used ranged from 500 to 50,000 rad. After irradiation the cells were seeded on Tamiya's solid medium and incubated. The relationship between the survival and mutation rates and doses used was investigated by the method of macrocolonies, and death at different stages of development of the cells was analyzed by the method of microcolonies [1].

Results of the experiments to determine the relationship between the survival rate of Chlorella and the dose of protons and γ -rays are plotted in Fig. 1 on a semilogarithmic scale. The experimental results were analyzed by statistical methods. Lines of regression of the logarithm of the survival rate, in %, against dose, calculated for straight-line portions of the dose-effect curve, are shown on this figure. All the experimental results lie within 95% confidence limits.

The regression equation for protons is as follows: $y = 2.154 - 0.063x$, where y represents the logarithm of the survival rate of Chlorella for a dose x . The value of LD_{50} is determined from the regression equation, and is 7.2 krad.

Data for the survival rate of Chlorella during exposure to different doses of γ -rays were very close to the results obtained during irradiation of Chlorella with x-rays [5]. The regression equation for the action of γ -rays is as follows: $y = 2.153 - 0.041x$. From this equation, LD_{50} for γ -rays is 11.5 krad.

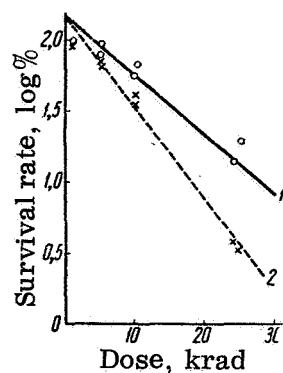


Figure 1. Survival Rate of Chlorella Cells after Exposure to γ -rays (1) and Protons (2).

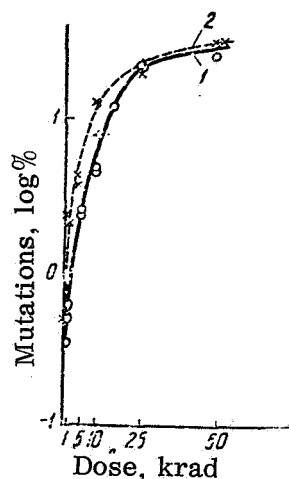


Figure 2. Mutation Rate of Chlorella as a Function of Dose of γ -rays (1) and Protons (2).

TABLE 1. Mutation Rate of Strain LARG-1 in Relation to Dose of Protons and γ -Rays

Dose, rad	Protons		γ -rays	
	Number of colonies	Mutations, %	Number of colonies	Mutations, %
Control	8115	$0,743 \pm 0,086$	10654	$0,623 \pm 0,076$
545	2825	$3,250 \pm 0,333$	3637	$1,280 \pm 0,187$
590	5522	$1,197 \pm 0,187$	9089	$0,880 \pm 0,098$
1 038	2228	$2,850 \pm 0,352$	3437	$1,380 \pm 0,200$
1 070	7291	$1,246 \pm 0,130$	9173	$1,035 \pm 0,106$
5 040	2061	$4,700 \pm 0,465$	4655	$3,110 \pm 0,254$
5 460	4318	$5,120 \pm 0,332$	7301	$3,095 \pm 0,202$
9 700	1726	$8,913 \pm 0,685$	3541	$5,580 \pm 0,385$
10 900	2878	$14,100 \pm 0,648$	4216	$5,000 \pm 0,336$
25 000	635	$20,936 \pm 1,610$	2098	$23,730 \pm 0,928$
25 700	261	$24,870 \pm 2,670$	1896	$27,040 \pm 1,020$
50 250	1335	$33,200 \pm 1,290$	1896	$27,040 \pm 1,020$

Commas represent decimal points.

Protons thus have a stronger inactivating action on Chlorella cells have γ -rays. The relative biological effect (RBE) of protons relative to γ -rays in our experiments is 1.60. Relative to x-rays, using data previously obtained [5], RBE for strain LARG-1 is 1.52. When a Chlorella culture was irradiated with protons in a dose of 25 krad and the cells were subsequently fed in a liquid medium under standard conditions of cultivation (illumination about 10,000 lx, $t = 34^\circ$, ventilation with a mixture of air and 1.52-2.0% CO_2), the reproductive power was restored on the 16th day.

The relationship between mutation rate of cells of strain LARG-1 and dose is shown in Fig. 2 and Table 1. The dose—mutation rate curves for the cells obtained during exposure to γ -rays and protons are similar in shape.

Initially the percentage of mutations rises proportionally to the dose, after which saturation takes place. Up to a dose of 10 krad inclusive, the mutagenic action of protons exceeds that of γ -rays significantly, but later the difference is no longer significant. However, comparison of the mutation rate induced by γ -rays and protons for equal survival rate shows that γ -rays cause a higher percentage of visible mutation, for with a survival rate of 50% γ -rays induce 7.8% of mutations compared with 3.7% induced by protons. It thus follows that γ -rays give a higher ratio of visible to lethal mutations than protons.

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STUDY OF REGENERATION OF AIR AND WATER BY HIGHER PLANTS IN A CLOSED SPACE

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A promising method of human life support during long space flights is the use of autotrophic organisms for the regeneration of food, water and oxygen.

The object of the present investigation was to study gas and water exchange of a series of cultivated vegetables likely to be used in spacecraft and interplanetary stations.

Determination of gas exchange has most frequently been carried out on individual leaves, and this does not permit assessment of oxygen production and carbon dioxide assimilation by whole plants, still less by cenoses [3, 7, 8, 10, 13].

To construct reliable systems on the basis of photoautotrophic organisms a precise analysis of the gas exchange of the plants to be cultivated in spacecraft cabins in relation to their age, planting density, time of day, level and duration of illumination, and also temperature, humidity and other factors of the external environment must be made. Characteristics of the gas exchange of plants can be obtained most reliably and accurately not by periodic measurements, but by continuous recording of the intensity of photosynthesis and respiration of the plants [1, 11-14].

It is also essential to investigate water metabolism (transpiration and water absorption) of plants grown in airtight spaces equally carefully and under different external conditions in order to determine quantitatively the ability of the plant to regenerate water. The chemical characteristics of transpiration water are hardly mentioned in the literature. For our purposes it is absolutely essential to have such an analysis from the point of view of its suitability for drinking by man. /525

To study the gas and water exchange of some potentially suitable plants for ecological systems we carried out a series of experiments with continuous recording of these processes for 3-5 days. The experiments were carried out in a specially constructed hermetically sealed apparatus in which conditions favorable for activity of living plants as regards temperature, humidity, light, carbon dioxide and supply of minerals were maintained.

DESCRIPTION OF APPARATUS

The apparatus consists of the following main units (Fig. 1):

- 1) An airtight assimilation chamber;

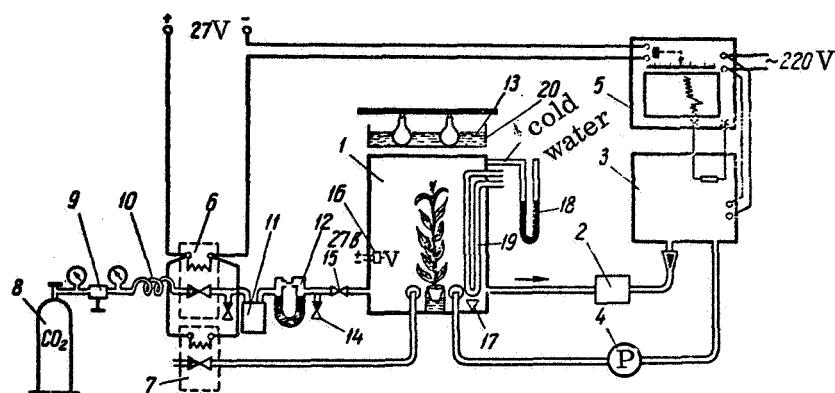


Figure 1. Theoretical Scheme of Apparatus for Studying Gas and Water Exchange of Higher Plants: 1) Chamber Containing Plants; 2) Gas Dryer; 3) Gas Analyzer; 4) Pump; 5) EPP-09-M2 Potentiometer; 6) Electromagnetic Valve for CO₂ Supply; 7) Electromagnetic Valve for Dissipating Excess Pressure; 8) CO₂ Cylinder; 9) Pressure Reducer; 10) Metal Capillary Tube; 11) Receiver; 12) Rheometer; 13) Source of Light; 14) and 15) Clamps; 16) Fan; 17) Water Collector; 18) Manometer; 19) Cooler; 20) Water Screen.

- 2) A unit for automatic supply and recording of carbon dioxide;
- 3) A cooling system for the chamber;
- 4) A lighting system;
- 5) A control unit and auxiliary equipment.

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The assimilation chamber, 180 liters in capacity and 28 dm² in area, is made of organic glass and secured hermetically to a plastic floor by means of flanges, bolts and rubber washers.

A hygrograph and laboratory thermometer for checking the air temperature and humidity are placed in the chamber. A fan ensures better mixing of the gases in the chamber. Two pipes are provided for connecting the inlet and outlet of the gas analyzer. The assimilation chamber is connected to a manometer. A special pipe is connected to a flask for collecting condensed moisture.

Changes in carbon dioxide concentration are recorded by a "URAS" infrared optico-acoustic gas analyzer with measuring scale from 0 to 0.5% and a relative accuracy of measurement of 1.6%.

Depending on the character of the investigations, it was necessary not only to record the CO₂ concentration in the chamber but also to maintain it at a certain level. This was done by replacing the recording system of the gas analyzer by a type EPP-09-M2 electrotonic potentiometer, which is not only an automatic writer, but also a position regulator. On receipt of a signal from the potentiometer, CO₂ was supplied from the cylinder through an electromagnetic valve EKR-3.

This apparatus provides a means of recording the carbon dioxide concentration in the system over a wide (0-5%) and also a very narrow (0-0.01%) range. To ensure better mixing, the carbon dioxide is supplied through a pipe into the upper part of the chamber. Air in the chamber is mixed by a fan.

To dissipate excess pressure from the chamber resulting from addition of carbon dioxide a second electromagnetic EKR-3 is used, and opens simultaneously with the first on receipt of the signal from the potentiometer. The principle of automatic recording of CO_2 in the system was developed and described by V.I. Rozhdestvenskiy, V.G. Chuchkin and A. F. Kreshnin [9].

To regulate the rate of carbon dioxide supply a pressure reducer, capillary tube and rheometer are used. Circulation of the air through the closed circuit from the chamber to the gas analyzer is effected by a membrane pump and maintained at the level of 30 liters/hour.

To regulate the temperature in the chamber within the limits of $23 \pm 3^\circ$, and to control condensation of moisture and maintain the humidity at not more than $80 \pm 10\%$, a cooling system of brass tubes through which cold tap water circulates is provided.

In addition, if the temperature rises above 26° the chamber is cooled by two alternately operating air-conditioning units of the "Azerbaydzhani-2" type.

The source of light in the experiment consisted of type 3N-8 incandescent lamps. To remove infrared radiation the lamps were immersed in a water screen with a water layer of 30 cm. Water from the town supply is fed into the water screen through two EKR-3 electromagnetic valves operated by a contact thermometer when the water temperature is 25° . The hot water runs away to waste through the top pipe.

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The intensity of physiological radiation was measured by a differential thermopile, and at the level of the topmost leaves it was $300 \pm 10 \text{ W/m}^2$.

EXPERIMENTAL METHOD AND CALCULATION OF GAS EXCHANGE OF PLANTS

To study the regeneration of air and water the following plants were chosen: culinary beetroot variety Bordeaux, sugar beet variety Belaya (White), carrot variety Nantes, cabbage variety No. 1, Chinese cabbage variety Khibinskaya, potato variety Lorkh, pea variety Pioneer (Pioneer), haricot bean variety Sakharaya (Sugary), radish variety pink-red with white tip, lettuce variety Berlin, beans variety Russkiye Chernyye (Black Russian), soybean variety Primorskaya 529 (Maritime 529).

The plants were grown in flower pots filled with vermiculite. The pots with the plants were placed in large vessels containing Abele's nutrient solution (a full range of major and trace elements).

The plants were grown with illumination for 18 hours (from 6 AM to midnight) and 6 hours darkness.

Most plants were used in the experiment at the age of 2 months, but the Chinese cabbage, lettuce and radish were grown for 30 days before the experiment. On reaching this age several plants were placed in the assimilation chamber for 3-5 days to determine the intensity of gas and water exchange.

In all the experiments the total leaf area of all the experimental plants was approximately three times the floor area of the assimilation chamber.

After the plants had been placed in the apparatus the airtightness of the whole system was carefully checked.

At the beginning of the experiment the optimal CO_2 concentration was determined for each culture within the range 0.05-0.5%. For this purpose, the intensity of photosynthesis of the experimental plants was calculated for different CO_2 concentrations in the system and the saturation level of photosynthesis with respect to CO_2 was determined.

For most of the investigated species saturation took place at 0.15-0.3% CO_2 . The concentration found was maintained during the following days of the experiment.

The gas exchange of the plants was calculated from the formula:

$$P = \frac{dv (P_1 - P_2)}{100 \cdot S \cdot \Delta t},$$

where P represents the intensity of gas exchange in $\text{mg CO}_2/\text{dm}^2$ leaf/hour; v /528
the volume of the system (subtracting the volumes of articles within the chamber), P_1 the initial CO_2 concentration (in %); P_2 the final CO_2 concentration (in %); Δt the time of change of CO_2 concentration (in hours); S the area of the leaves (in dm^2); d the specific gravity of CO_2 (in mg/liter).

A sample recording on the potentiometer tape of the change in CO_2 concentration during photosynthesis in sugar beet is given in Fig. 2. To calculate the intensity of photosynthesis over each segment of the curve the initial and final CO_2 concentrations were determined. In this particular case P_1 was 0.435% CO_2 , P_2 0.325% CO_2 and Δt 10 min. As Fig. 2 shows, the intensity of photosynthesis per hour was calculated as the mean of four repetitions. Over a narrower range of CO_2 concentration in the system (for example, $\Delta C = 0.05\%$), the number of repetitions can be increased to 8 or 9.

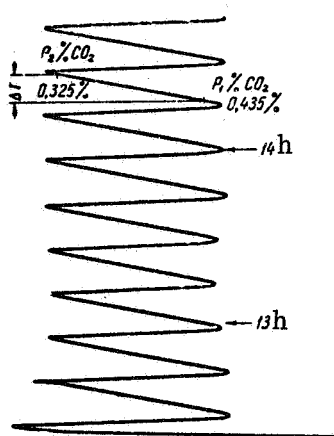


Figure 2. Sample Recording of Change in CO_2 Concentration During Photosynthesis in Sugar Beet.

The leaf area was determined as follows: outlines of the leaves were traced on squared paper, cut out and weighed. Subsequent calculations were made on the basis of the weight of 1 dm^2 of squared paper.

After each experiment the quantity of water in the water collector was determined and the water itself was analyzed chemically.

EXPERIMENTAL RESULTS

Our experiments using different vegetable plants showed that the mean values of carbon dioxide assimilation calculated per dm^2 leaf area varied for the different species (Table 1).

As Table 1 shows, the most intensive assimilation of carbon dioxide, up to $30\text{--}37 \text{ mg}/\text{CO}_2/\text{dm}^2$

was found with beetroot and sugar beet. Low carbon dioxide assimilation of the order of $6\text{--}10 \text{ mg CO}_2/\text{dm}^2 \cdot \text{h}$ was obtained with lettuce, haricot bean and pea. With this group of external factors in which the experimental plants were grown, low values of intensity of photosynthesis were obtained. This may be attributed to the fact that in our experiments gas exchange was not determined for each leaf separately but for a complete group of plants. In this case the plants constitute a complex optical system of leaves, arranged in several layers with a total leaf area on the average more than three times greater than the floor area of the assimilation chamber. With illumination only from above, as in these experiments, all the leaves of the plants were not in identical conditions of irradiation. Only the topmost and peripheral leaves received adequate light, while the shaded leaves received inadequate illumination. The intensity of luminous flux passing through the thickness of one leaf is only $0.1\text{--}0.25$ of the initial value of the direct radiation [5]. Consequently, if the topmost leaves received $300 \text{ W}/\text{m}^2$ the intensity of illumination of the shaded leaves was several times smaller, and this resulted in a corresponding decrease in the rate of CO_2 assimilation.

To determine the relationship between the intensity of gas exchange and the total leaf area of the plants and, consequently, on their intensity of illumination, special experiments were carried out with Chinese cabbage.

Three plants aged two months with identical leaf area (20 dm^2 each) were chosen for the experiment. Two experiments were performed. In the first the intensity of CO_2 assimilation by the cabbage was studied when one plant was placed in the experimental chamber, i.e., under conditions of good illumination of the complete leaf surface. In this case the carbon dioxide assimilation

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TABLE 1. Intensity of Gas Exchange of Experimental Plants (mean values during period of daylight)

Plant	Intensity of CO ₂ absorption mg/dm ² /hour	Total leaf area, dm ²	Ratio between leaf area and area sown (28 dm ²)	CO ₂ assimilation per hour calculated per total leaf area	
				Area sown 28 dm ²	Area sown 1 m ²
Lettuce	8	109	3,9	0,87	3,11
Chinese cabbage . . .	12	84	3,0	1,0	3,6
Radish	16	75,4	2,7	1,2	4,3
Pea	10	70	2,48	0,7	2,5
Beetroot	30	78,4	2,8	2,35	8,5
Sugar beet	37	71,4	2,6	2,64	9,42
Haricot bean	6	81	2,83	0,48	1,74
Soybean	26	68,8	2,53	1,78	6,48
Carrot	21	80	2,85	1,68	5,99
Bean	12	97	3,43	1,16	4,15
Cabbage	15	74	2,63	1,11	3,96
Potato	12	89	3,17	1,07	3,81

Commas represent decimal points.

calculated per dm² leaf area was 22 mg CO₂/hour. In the second experiment three plants with a total area of 56 dm² were placed in the chamber and the intensity of assimilation per dm² leaf surface was reduced by half (Fig. 3). It must be remembered that these experiments were carried out with identical light, CO₂ concentration, temperature, and other conditions. On the basis of these experiments it can be assumed that a leaf area not exceeding the area of the assimilation chamber gave the highest work intensity. Consequently, under the experimental conditions when the total leaf area was on the average three times greater than the area of the chamber, the plants did not completely utilize their potential capacity because of inadequate illumination of the complete leaf surface. It may be considered that if uniform illumination of all leaves of the plants could be ensured by placing sources of light within the cultivated area, the intensity of gas exchange of the plants could be considerably increased.

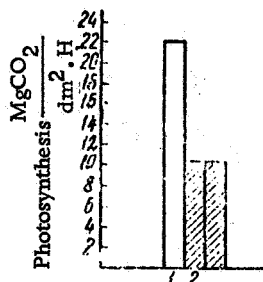


Figure 3. Intensity of Photosynthesis of Chinese Cabbage for Leaf Areas of 20 (1) and 40 dm² (2).

To establish the essential sowing areas to provide for the oxygen demands of the spacecraft crew, the gas exchange of all plants in the experiment must be known, calculated per total leaf area.

It follows from Table 1 that most vegetable plants (potato, cabbage and Chinese cabbage, beans, radish), if an area of 1 m² is sown, assimilate on the average about 4 g CO₂ per hour, while for beetroot and sugar beet these values are doubled.

To calculate the gas exchange of the plants in the 24-hour period, the diurnal rhythm of CO₂ assimilation and oxygen excretion must be taken into account.

A characteristic feature of the diurnal course of gas exchange of most of the investigated plants is the midday depression, lasting 3-4 hours starting from 11 A.M. to noon. A typical diurnal course of gas exchange of most experimental plants as exemplified by beetroot is shown in Fig. 4. Analysis of the curve reveals that immediately after the period of darkness the intensity of carbon dioxide assimilation rises for 4-5 hours. This is followed by depression when the assimilation falls by 4-5 mg CO₂/dm²·h, and between 3

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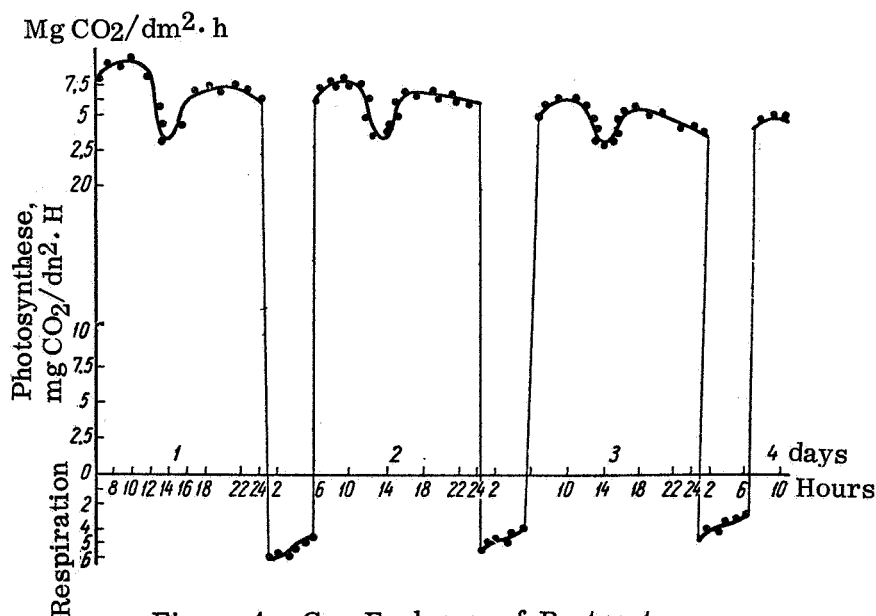


Figure 4. Gas Exchange of Beetroot.

4 P.M. it rises again. The decrease in assimilation at midday is probably associated with accumulation of products of photosynthesis in the leaves and interference with their outflow into other parts of the plant. The size of this midday "trough" of carbon dioxide assimilation depends on the intensity of illumination (Fig. 5). For sugar beet with a luminous flux of 300 W/m^2 the intensity of gas exchange at midday falls by $3\text{--}4 \text{ mg CO}_2/\text{dm}^2 \cdot \text{h}$, whereas for sugar beet grown in 150 W/m^2 , the trough is hardly visible ($1\text{--}2 \text{ mg CO}_2$).

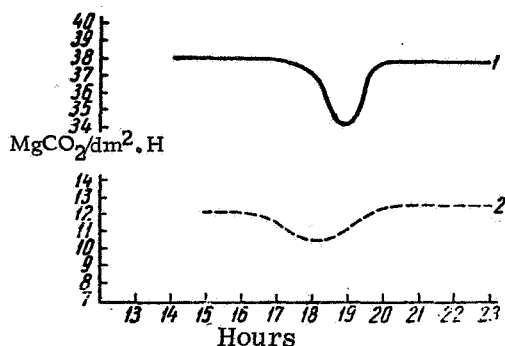


Figure 5. Diurnal Course of Photosynthesis of Sugar Beet in Different Intensities of Light. 1) 300 and 2) 150 W/m^2 .

It is an interesting fact that a change in illumination intensity from 150 to 300 W/m^2 should cause an increase in assimilation of carbon dioxide of three times or more.

To determine the 24-hour productivity of higher plants, besides CO_2 assimilation during daylight, the gas exchange of the plants during the night must also be taken into account. At night, in the absence of light, processes of respiration take place in plants, during which the plants excrete carbon dioxide and assimilate oxygen.

Nocturnal gas exchange, like diurnal, has a specific rhythm. In our experiments the character of the gas exchange curves during the night showed little difference for the various species. At the beginning of the night CO_2 excretion was most intensive and thereafter it gradually decreased, falling to a minimum by morning.

As Table 2 shows, the intensity of respiration differs in higher plants: the higher the carbon dioxide assimilation by day, the more intensive its excretion by night. In the case of beetroot, for example, the mean intensity of assimilation was $30 \text{ mg CO}_2/\text{dm}^2 \cdot \text{h}$, while at night the mean excretion was $5.5 \text{ mg CO}_2/\text{dm}^2 \cdot \text{h}$. For lettuce, the intensity of diurnal carbon dioxide assimilation was $8 \text{ mg CO}_2/\text{dm}^2 \cdot \text{h}$ and the nocturnal excretion was $2.4 \text{ mg CO}_2/\text{dm}^2 \cdot \text{h}$.

The relationship between CO_2 assimilation by day and its excretion by night can be seen in Fig. 4. Calculations show that for most species under the experimental conditions used the mean nocturnal excretion of carbon dioxide was $4\text{--}7\%$ of the intensity of its assimilation during daylight (Table 3).

By integrating the areas of the curves for the course of intensity of 24-hour gas exchange of the plants (Fig. 4), plotted from readings on squared paper tape,

TABLE 2. Intensity of Gas Exchange of Various Vegetable Plants by Night (in $\text{mg CO}_2/\text{dm}^2 \cdot \text{h}$)

Plant	Time, hours					
	1	2	3	4	5	6
Lettuce	3,03	3,18	2,89	2,2	1,82	1,50
Chinese cabbage . . .	2,70	2,27	1,83	1,62	1,11	1,0
Sugar beet	5,72	5,70	4,44	4,13	2,19	1,89
Beetroot	10,32	7,80	6,11	4,13	2,90	1,6
Soybean	5,38	5,44	4,90	4,69	4,23	4,15
Beans	4,68	3,71	3,21	2,80	2,51	1,71
Radish	3,17	2,90	2,85	2,34	1,95	1,73
Pea	2,15	2,20	2	1,73	1,50	1,45
Carrot	5,28	5,17	4,70	4,00	3,50	2,70
Potato	3,68	3,40	2,95	2,80	2,48	1,95
Cabbage	3,10	3	2,17	1,93	1,25	1,11
Haricot bean	2,75	2,60	2,62	2,40	2,0	1,65

Comma represent decimal points.

the gas exchange of the plants during the days of the experiment can be calculated. These results are given in Table 3.

Highest values of carbon dioxide assimilation were found with beetroot and sugar beet, namely $128-145 \text{ g CO}_2/\text{m}^2$. Assimilation of the order of $70-90 \text{ g/m}^2$ was observed with beans, soybean and carrot.

Under these experimental conditions, i. e. , with humidity of the order of 80-90%, temperature $20-26^\circ$, intensity of luminous flux of 300 W/m^2 , and with an air circulation speed of 30 liters/hour and the other factors provided in the experiment, the intensity of transpiration was low, namely $19-40 \text{ g/m}^2$ leaf area (Table 4).

With these values of transpiration intensity, the studied plants would yield 1.5-2.5 liters water per square meter of sown area per day and would completely satisfy the water requirements of a map. Furthermore, the quality of the condensate, as shown by preliminary analyses carried out by S. V. Chizhov

TABLE 3. Gas Exchange of Various Vegetable Plants per 24 Hours Calculated per Total Leaf Area

Plant	Quantity of CO ₂ , g/24 h		Ratio of respiration to photosynthesis, %	CO ₂ assimilated in 24 h	
	Assimilated over 18 h	Excreted over 6 h		28 dm ²	1 m ²
Lettuce	14,16	1,3	7,0	12,86	45,9
Chinese cabbage . . .	16,0	0,9	5,6	14,1	50,36
Radish	19,5	0,9	4,6	18,6	60,43
Pea	11,4	0,71	6,2	10,69	38,18
Beetroot	38,1	2,35	6,1	35,75	127,7
Sugar beet	42,82	2,28	5,3	40,54	144,7
Haricot bean	7,78	1,16	5,7	6,62	23,64
Soybean	28,84	1,65	5,7	27,19	97,10
Carrot	26,62	1,92	7,2	24,7	89,28
Beans	19,88	1,45	7,0	18,43	65,79
Cabbage	17,9	0,84	4,7	17,06	60,92
Potato	17,36	1,09	6,1	16,27	58,10

Commas represent decimal points.

TABLE 4. Quantity of Water Obtained during Cultivation of Higher Plants

Plant	Total leaf area, dm ²	Quantity of water from 28 dm ² sown g/h		Quantity of water, g/day from sown area of	
		Light period	Dark period	28 dm ²	1 m ²
Lettuce	109,0	24,00	12,40	506,4	1891
Chinese cabbage . . .	84,0	35,60	12,00	712,8	2546
Radish	75,4	21,83	8,12	441,6	1577
Pea	70,0	15,78	9,07	338,4	1208
Beetroot	78,4	28,03	17,28	608,2	2172
Sugar beet	71,4	27,00	13,16	564,9	2017
Haricot bean	81,0	19,50	10,70	415,2	1482
Soybean	68,8	25,29	10,54	518,4	1851
Carrot	80,0	25,36	15,52	549,6	1964
Beans	97,0	31,99	12,44	650,4	2322
Cabbage	74,0	33,23	14,72	722,4	2580
Potato	89,0	19,57	12,10	424,8	1517

Commas represent decimal points.

and co-workers, differs only slightly from the accepted standards for drinking water.

It must be stressed yet again that the data given in this paper for the gas exchange and water excretion of the selected plants are characteristic of mature plants with a developed leaf surface and grown as a single crop. When these indices are calculated for the conditions of the spacecraft greenhouse, allowance must be made for the relative percentages and planting density of the various vegetable plants and also the relative ages of the plants when grown in the conveyer.

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